A rain of L-Chondrites in the Thorsberg quarry at Kinnekulle, southern Sweden

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Abstract. About forty meteorites have been found in the first systematic search for fossil meteorites in an active quarry in Lower/Middle Ordovician marine limestone in southern Sweden. The total original mass of these meteorites amounts to 7.7 kg. They represent at least 12 different falls over a seafloor area of 6000 m^2 during 1.75 million years. Thereby the quarry is one of the most meteorite dense areas known in the world. Geochemical analyses indicate that all or most of them are ordinary chondrites and probably L-chrondrites. Obviously the flux of meteorites was one to two orders of magnitude higher as today. This matter of fact reflects possibly a collision of asteroids in the Ordovician which leads to the higher bombardment of the earth.

1. Introduction

When the planets had reached their final size by accretion, a rest of relic material was floating through the inner part of the solar system, resulting in the bombardment of the planetary bodies which had their regular paths. Through this late heavy bombardment most of the large craters on the moon where built. About three billion years ago, this attack was largely finished and the collision rates decreased to the todays standard. But even today a considerable amount of extraterrestrial bodies hit our home planet, about thousand tons per day. And every millions of years, the earth is striked by objects which reach a size of about 100 meters up to some kilometers. Such objects, which are normally not disrupted by passing the atmosphere, collide with the earth with a velocity between eleven and seventy kilometers per second. Connected with these impacts most of the kinetic energy is transformed into heat energy, leading to a complete evaporation of the projectile. Only a big crater is retained.

While most of these craters on earth were masked and destroyed by processes of erosion and tectonics, on other solid bodies without or only with a little atmosphere, like mars, mercury or our moon, they were conservated through long times. Much more frequent as such large bodies, small objects reach the earth: Particles of mm-size glow and evaporate as falling stars in the atmosphere. Even smaller particles are broken to pieces when passing outer zones of the atmosphere. All this material can potentially be sampled and analyzed in deep see sediments or ice cores. Occurrences of meteorites with a size of about any centimeters or meters are rare. However, more then 30.000 meteorites of this type, mostly found in deserts or at the polar ice caps, can be visited in mineralogical collections all over the world. They are considered being the “space probes of the poor man”, but in fact they are a lot more than that.

Most of the meteorites are fragments of asteroids, which are situated between the paths of Mars and Jupiter. In this asteroid belt the density of such objects is much higher then in the rest of the solar system. Thereby collisions are more frequent and the result is the formation of smaller fragments of these often more then 100 km large asteroids. Nowadays collisions of km-sized bodies are very rare, while a crash of some m-sized objects is clearly common, due to the fact, that such objects simply are more abundant. The gravitational force of the gas giants Jupiter and Saturn has a kind of security function for the earth, because they steer the paths of the incoming objects and catch them in some cases.
Typically, great asteroid pieces require from their birth as the result of a collision some ten millions of years to reach our planet. But for smaller meteorites with only a few meters in diameter, a change in the path parameters induced by an asteroid collision results in an acceleration, so that they can reach the pathway of the earth in a million or some hundred thousands of years.

The distribution of meteorite craters on moon, mars and mercury give us informations about the impact rate of extraterrestrial bodies in the past. It shows that over the last 3.5 billion years the influx of extraterrestrial material was approximately constant. This does not correspond to recent statistics, because most of todays findings come from geological young periods of time, mostly from the last 2 million years. The reasons for that discrepancy are the intensive weathering processes, which destroyed most of the older evidences of meteorites.

But there is one important exception: In the 1990s a working group around Birger Schmitz from the University of Lund discovered the relicts of fossil meteorites in a Swedish quarry, interbedded in limestone of the Lower/Middle Ordovician. This abundance of meteorites is more than 100 times larger as it has been estimated from the actual falling rates.

2. Geological Setting

The Thorsberg quarry at Kinnekulle is situated in southern Sweden near the so called Vänern Lake (Fig.1). In the Ordovician time about 480 - 470 million years ago, the arrangement of the landmasses were totally different as today.

Baltica and Scandinavia were linked together to a microcontinent, which had a low-latitude-position. These landmasses were covered by a huge epicontinental sea, in which the sediments were deposited.

Fig.1. Location of the Thorsberg quarry at Kinnekulle near the Vänern Lake in southern Sweden (Schmitz et. al, 2006).

The active part of the Thorsberg quarry spans a 3.2 m thick section of Lower/Middle Ordovician marine limestone. Twelve prominent beds, 11–62 cm thick, can be discerned. Each has a name traditional used by the quarry workers. The beds occur in a horizontal position and have not been affected by tectonics. The lower 80 cm and the upper 1 m of the section consist of red limestone, separated by 1.4 m gray limestone (Fig.2).

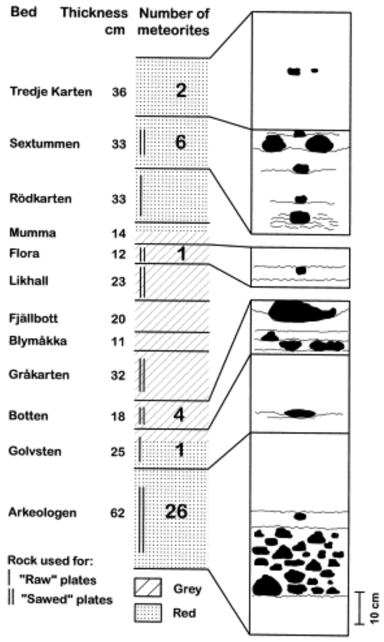

Fig.2. Quarried beds and meteorite distribution in the Thorsberg quarry. Column at the right shows the intra-bed distribution of the meteorites. The exact positions of the meteorites from the Tredje Karten bed and most of the meteorites from the Arkeologen bed are not known. Only half of the section is used for production of plates, the rest being crushed and not searched for meteorites (Schmitz et. al, 2001).

According to traditional stratigraphic nomenclature the section in the Thorsberg quarry belongs to the Lower Ordovician. The International Commission on Ordovician Stratigraphy has suggested to revise the definition of the Lower/Middle Ordovician boundary, implying that the section would instead be in the Middle Ordovician series.

The quarried Orthoceratite limestone (Fig.3) was deposited during the Arenigian to Llanvirnian Period in an epicontinental sea that covered several 100.000 km^2 of the Baltoscandian Shield. This condensed limestone formed at an average rate of one to a few mm per thousand years. The deposition was variable, changing from long periods of non-deposition and hardground formation to more rapid pulses of sedimentation. Biostratigraphically, the quarried section belongs to the Amorphognatus variabilis–Microzarkodina flabellum conodont subzone. Based on an average sedimentation rate of 2 mm per thousand years for the Arenigian limestone at Kinnekulle the section is estimated to represent a time span of ≤ 1.75 million years.

Fig.3. Large plate (70×110 cm) of limestone sawed parallel to seafloor surface. Several nautiloid shells accumulated on a hardground surface in the vicinity of the Österplana Ark 023 meteorite (3.5×4.5 cm). The iron in the red limestone around the meteorite has been reduced, therefore a halo of lighter gray limestone has formed (Schmitz et. al, 2001)

The different beds and sublayers in the Thorsberg quarry are of different industrial quality. A major part of the section consists of high-quality limestone used for the production of sawed plates sold as floor plates, window sills, stair cases etc. Some intervals of lower quality are primarily used as raw garden plates or crushed for production of cement or lime for agriculture. Some intervals are only used for production of crushed rock. Blocks of limestone (ca. 1.25×2×0.5 m) are recovered and transported to the nearby sawing factory.

The quarrying is performed in two steps. First the beds above the basal Arkeologen bed are removed and thereafter the Arkeologen bed, that is under the ground water table, is quarried in small basins from which the water has to be pumped. From the end of 1992 to the end of 2000 an area of 6000 m^2 of the beds overlying the Arkeologen bed and 2700 m^2 of the Arkeologen bed were quarried.

The fossil meteorites, which range in size between 0,7 and 20 cm, can readily be identified by macroscopical examination, despite being completely pseudomorphosed primarily by calcite, barite and phyllosilicates. The only relict mineral phases are chromite and chromian spinel. For all 14 meteorites from layers above the Arkeologen bed and for 16 of 26 meteorites from the Arkeologen bed visual identification was confirmed by bulk-meteorite platinum group element or osmium isotope analyses and/or element analyses of relict chromite grains.

3. Classification of chondrites

Meteorites in general can be subdivided into four main groups: There are the iron meteorites, the stony-iron meteorites and the achondrites, which all go back to well differentiated asteroid parent bodies. And on the other hand, there are the stony meteorites or chondrites, which have their origin in undifferentiated, so called primitive parent bodies. Average differentiated bodies can be classified as additional group: These are for example the acapulcoites or the lodrantites. Examples for iron meteorites are hexaedrites and octaedrites, while pallasites and mesosiderites are classical stony-irons. With the exception of the achondrites, all these meteorites are composed of a matrix and so called chondrules. These are grain-like particles, which are the major textural component of chondrites and have igneous properties in that they formed from a molten or partially molten state. Mostly they have spherical, subspherical and sometimes ellipsoidal shapes.

The chondrites are a diverse suite of meteorites, and are subdevided into 12 well established groups. These are defined by properties including their bulk chemistries, isotopic compositions, oxidation states, and proportions of individual components. The primary divisions of chondrite classification are the carbonaceous (C), ordinary (O), and enstatite (E) classes, each of which contains distinct groups that are closely related (Fig.4).

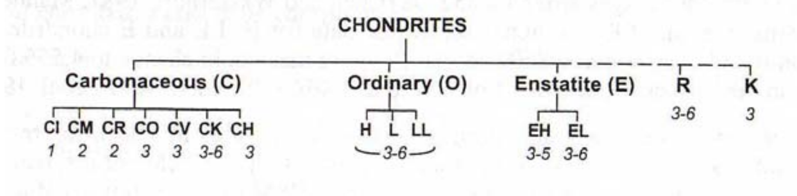

Fig.4. Classification of chondrite classes and groups. Petrologic types within each group are in italics (Papike, 1998).

The O-class is divided into three groups, H, L and LL. H-chondrites have high total Fe, L-chondrites have low total Fe contents, and LL-chondrites have low metallic Fe relative to total Fe, as well as low total Fe contents (Fig.5).

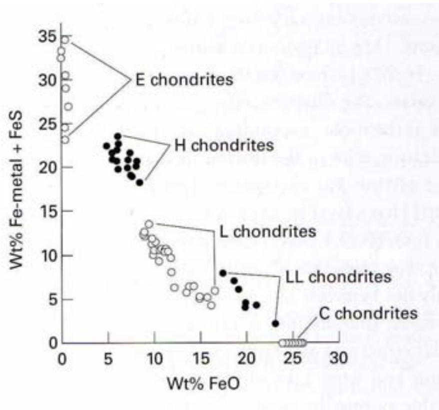

Fig.5. This graph plots the weight percent oxidized iron against the weight percent of iron metal plus FeS in ordinary chondrites observed to fall and recovered shortly thereafter. A clear division of the three classes is obvious and the ordinary chondrite class is divided into its three groups, H, L, LL. (Norton, 2002).

Another classification that is based on the petrologic-chemical properties is the distinction into six petrographic types (Van Schmus-Wood criteria). The main characteristic for distinction is the texture of the chondrules: Type 1 has no chondrules, while type 2 and 3 show very sharply defined chondrules. Type 4 has well-defined chondrules and in type 5 and type 6 chondrites there are chondrules which were readily or poorly defined. The second important marker to distinguish is the matrix texture: Type 1 shows an all fine-grained, opaque matrix, while the grade of recrystallization increases with the type 2 to 6. Other criterias are for example the homogeneity of olivin and pyroxene compositions or the bulk carbon or bulk water content, which both degrease in higher groups.

Recent studies show, that in most ordinary chondrites chromite is a common trace mineral (0.05-0.5 wt%), whereas it is rare or absent in carbonaceous chondrites and enstatite chondrites as well as iron meteorites (Schmitz et. al, 2001). In all fossil meteorites inspected, chromite grains are common and have chemical compositions indicative of ordinary chondrites. The majority of the fossil meteorites plot in the low MgO and Al_2O_3 and high TiO_2 fields indicative of recent L and LL chondrites.

4. Isotopic dating with ^{40}Ar and ^{40}K

The meteorites show large crystals in a fine-grained matrix. ^{40}K, the mother isotope of ^{40}Ar is concentrated within these finer parts. During the impact metamorphism, which was connected with the disruption of a potential L-chondrite parent body 480 - 470 million years ago (Schmitz et al., 2005), the heating of the rock leads to a degassing of the noble gas argon. In fact of that, the ^{40}Ar isotopes which primary exist, were lost.

From that point, when the radiometric clock was re-set to zero, the content of ^{40}Ar increases again, caused by the radioactive decay of ^{40}K. Additionally there is also incompletely degassed, so called relic ^{40}Ar originated from a younger event before the impact. It's critical, but with the help of another isotope, ^{36}Ar, it can be identified (Fig.6).

This is only possible, because both, the relic ^{40}Ar and the ^{36}Ar, were mobilized during a hypothetically collision of asteroids. Caused by the same chemical properties, both isotopes belong to the noble gas argon, both were catched by other minerals. In case of only mobilization of ^{36}Ar, we would not have the chance to differentiate between the relic ^{40}Ar and the ^{40}Ar isotopes which were formed on the basis of the radioactive decay of ^{40}K. But luckily the relic ^{40}Ar was mobilized sufficiently, so that they were mixed with the ^{36}Ar isotopes, which gave them an isotopic marker. With that method the degassing age of the L-chondrite parent body was determined to 470±6 million years. For comparison, the age of the sediments, which include the meteorite material, was determined to 467±2 million years.

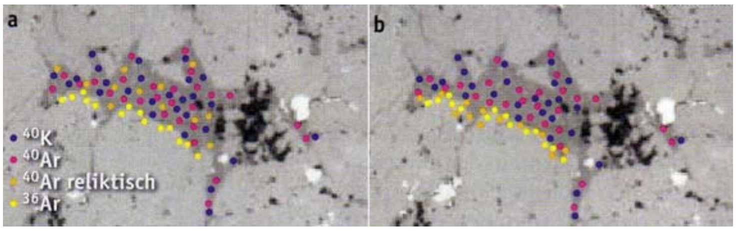

Fig.6. Two pictures showing the distribution of ^{40}K, ^{40}Ar, relic ^{40}Ar and the ^{36}Ar isotopes. In the left picture (a) only the ^{36}Ar is mobilized, while the relic ^{40}Ar is not mobilized sufficiently. So it is impossible to differ between ^{40}Ar that is formed on the basis of the radioactive decay and the relic ^{40}Ar. In the right picture (b) both, the relic ^{40}Ar and the ^{36}Ar isotopes are sufficiently mobilized. This allows to discriminate relic ^{40}Ar and the ^{40}Ar of the radioactive decay (Trieloff et. al, 2007).

5. Ordovician meteorite influx rates

The problem with the estimation of influx rates is the question how many fragments belong to the same fall-event. In theory, texture, cosmic-ray-exposure-gas, terrestrial evidence ages or the spatial distribution can be used as indications. But in reality all the meteorites of this age are extremely altered. As approximate value it's possible to say, that all meteorites found in the same horizon belong to the same event, because vertical migration is very unlikely. In dry areas it is known, that meteorites are destroyed after 20.000 to 30.000 years, the situation on the seafloor is still unknown. What we know is that 40 meteorites of 12 distinct horizons reached the earth within 1,75 million years on an area of about 6000 m^2.

As hypothesis we can say, that the sedimentation rate amounts to 2 mm per thousand years. Estimates of recent influx rates consider 80±40 meteorites with a mass of about 10 g per years on an area of 106 km^2. This agrees with an rate of 0,8±0,4 meteorites per 1,75 million years on area of 6000 m^2. But it is necessary to take into account that for the present study mostly big meteorites were considered. In recent times the influx rate of meteorites bigger than 100 g can be add up to 0,28 meteorites, while in the study this rate is 7 meteorites for the same area and the same time. That means, that the influx rate in the Ordovician was 25 times higher than today.

To avoid the problem with the assignment of the fragments to distinct falls, it is possible to compare the total mass of the meteorite material. For recent times there approximately 5,7 – 14,2 kg meteorite material per 106 km^2 and year have been estimated. This means 0,06 – 0,15 kg per 6000 m^2 and 1,75 million years. The fossil record shows 10,4 kg for the same time and area. This is 69 to 173 times more than the estimates for recent influx rates. But there are a lot more problems which should be considered: The 40 recognized meteorites represent only a little part of the meteorite material of the Thorsberg quarry. Only half of the sawed plates were used and not all the material could be investigated. A part of the limestone blocks were transported to other saw factories or was transformed into crushed rock. Little meteorites were not considered and it's a matter of likelihood to get a meteorite by sawing a limestone block. Another question is the preservation of the fossil meteorite material. However, the extremely high rates of about 1 meteorite per 100 m^2 remain a question.

Further studies in the same layers all over the world should give answers to these problems.

Correlations to large impact structures on the base of the isotopic dating and the petrological examination of the L-chondrites there is a possibility for a model: A collision in the asteroid belt in the Ordovician leads to the destruction of a big asteroid with a diameter of more than over 100 km. Thereby the rock fragments of both asteroids involved in the collision were hit for seconds by enormous shockwaves. The resulting heat, which was connected with these pressures of several hundred kilobars, leads to a partial melting of the material. After this extraterrestrial crash, gravitational anomalies had the effect that these fragments were guided to the course of the earth pathway. The result was a bombardment of our planet during the next 2 million years. The impact rate of kilometer-sized fragments was for the next 20 million years additionally higher: Eight great impact structures with ages between 470 and 450 million years have yet been identified in Baltica and Laurentia: Neugrund (Estland), Granby (Sweden), Ames (Oklahoma, USA): 470 million years; Kärdla (Estland), Tvären (Sweden), Lockne (Sweden): 455 million years; Slate Islands (Ontario, Kanada), Calvin (Michigan, USA): 450 million years (Fig.7 and http://www.unb.ca/passc/ImpactDatabase/europe.html).

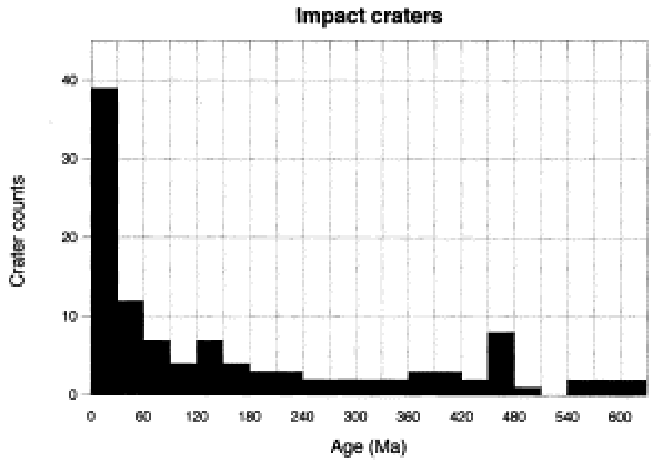

Fig.7. Histogram of ages of all dated craters in crater compilation complemented by information on ages of two craters (Lockne and Tvären). Note the small peak in crater ages in 450 – 480 million years (Schmitz et. al, 2001).

The energy of such impacts is enormous, so that global effects are probable. Due to the collision the influx of cosmic dust in the earth atmosphere increases and is high over millions of years. The climatic effects are still unknown. But in the Middle and Late Ordovician a big diversification of plants and animals is proved. If such a connection exists, such monumental collisions far away would have a big influence to the biosphere on earth.

6. Conclusion

It's a matter of fact that more then forty meteorites have been found in the Thorsberg quarry near Kinnekulle in southern Sweden. All these extraterrestrial bodies were found in a marine Orthoceratite limestone, which once was formed in an epicontinental sea. Thereby the quarry is one of the most meteorite dense areas known in the world.

Petrological analyses gave us the information that these meteorites mainly represent L-chondrites, which build one group in the classification of ordinary chondrites.

As we can see from isotopic studies, these meteorites show a shock metamorphism approximately between 470 and 480 million years ago.

The high influx rate represented by this chondritic material in Lower/Middle Ordovician times probably was connected with larger impacts identified on Laurentia and Baltica. A collision of large asteroids in the asteroid belt may have led to a disruption of the bodies and to changes of their path parameters. A large part of the asteroid fragments found their way to planet Earth and led to an increased bombardment of its surface during several millions of years.

Acknowledgements

I want to thank all the authors which wrote these good papers that gave me all the interest for these incredible and fascinating sciences.

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