SEVERAL RECENTLY DISCOVERED SUPPOSED ASTROBLEMES IN DALECARLIA, SWEDEN

Version 4.3

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SUMMARY

After having studied the well-known Siljan-astrobleme for several years and collected samples at a lot of up to date unknown sites, this author has identified several round structures of about 10 km diameter south of Lake Siljan in Dalecarlia (Sweden), in a belt trending from SSW to NNE. Narrow lakes of lunar shape, completed by circular trenches, often limit these structures. These structures very well could be astroblemes of their own, contemporary with the large Lake Siljan-astrobleme. Stony meteorites have the tendency to break up when passing the Earth’ atmosphere. In this case they fall down in a belt, the smallest first, larger ones later down the road.

In favour of this interpretation are about several hundreds of finds of impact-generated rock fragments like: Shatter cones, impact melts, suevites, pseudotachylites and secondary impact-generated rocks. These finds are very similar to those from the Siljan-astrobleme. The possibility has to be admitted, that the impact-generated fragments could have been transported to the round structures by Holocene ice flow. However, this is not possible: The facts for this statement are discussed in Chapter 8.

A further indication for the assumption that the round structures are astroblemes of their own, are large tilted sheets of rock in several of these, similar to tilted or vertical sheets of Ordovician carbonate within the Lake Siljan-astrobleme. In addition, there are two quarries within the supposed astroblemes, showing the shattered rock in situ at depth. Particularly the quarry in the Lake Långsjö-astrobleme (Pos. Aa) is important in this context. There the blasted rocks break along old cracks filled with a solidified melt, i.e. the old cracks are pseudotachylites. The position of the quarry is far too distant from the Lake Siljan-astrobleme to be affected by that. This strongly indicates, that the supposed Lake Långsjö-astrobleme really is an astrobleme of its own.

The final proof that at least some of these rings are astroblemes came on end of June 2008. It is at Lake Hummeln, described last in this report. There two completely different melts (different from Lake Siljan melts) show that the discovered blocks could not have been transported there by the Holocene ice-flow, but must be of local origin from an impact at that site.

In samples from at least two supposed astroblemes several cubic-centimetres-large pieces of Ordovician limestone have been found within reconstructed granite; these are pieces of calcite, mechanically thrown into the slurry, which later formed the reconstructed granite. These limestone pieces are not later veins of dissolved calcite. In normal granite calcite never can occur.

All these round structures are worthwhile a thorough investigation. A strew-field of possibly ten large astroblemes is to the authors' knowledge not known and would be a geological sensation. Up to date the Swedish Geological Community like universities, museums, the Swedish Geological Service and others have not shown any interest to follow up these finds. Hopefully foreign universities or researcher will show more interest.
This author will be pleased to guide foreign researchers to the sites.

The several years lasting work with the Siljan astrobleme and related astroblemes has led to understanding of the origin and forming of the Orsa sandstone. This is made up of the mater, ejected from the astrobleme crater.

1. PREFACE

An astrobleme is the crater made on the Earth by a falling meteorite or comet. Strange enough, Europe's largest astrobleme – the Lake Siljan astrobleme in central Sweden – has not been known before the 1960:s. Actually, the strange geology and botany of this region has been known for a long time, but not the reason for the ring dike of carbonate rock, which creates the fertile environment for ex. Orchides. Not before the mid 1960's – mainly due to the research done by Professor Thorslund – the geological community recognised, that the Siljan ring dike was created by a very large meteorite, falling around 377 ± 2 million years ago /1/. This ring has a diameter of roughly 40 km; the towns most nearby are Leksand, Rättvik and Mora.

Satellite pictures over Dalecarlia disclose, that the regional tectonics of this landscape consist of parallel straight ridges and valleys, trending NNW to SSE. Due to this, round structures are easily recognised.

A series of 10 such round structures has been located south of Lake Siljan, trending about 67° from SW to NE. Due to finds in the field, this author is convinced, that most of them are astroblemes and has given them the name of the nearest town or lake (all containing ring trenches filled with lakes). With the exception of Fjärden he has visited all, see Fig. 0.

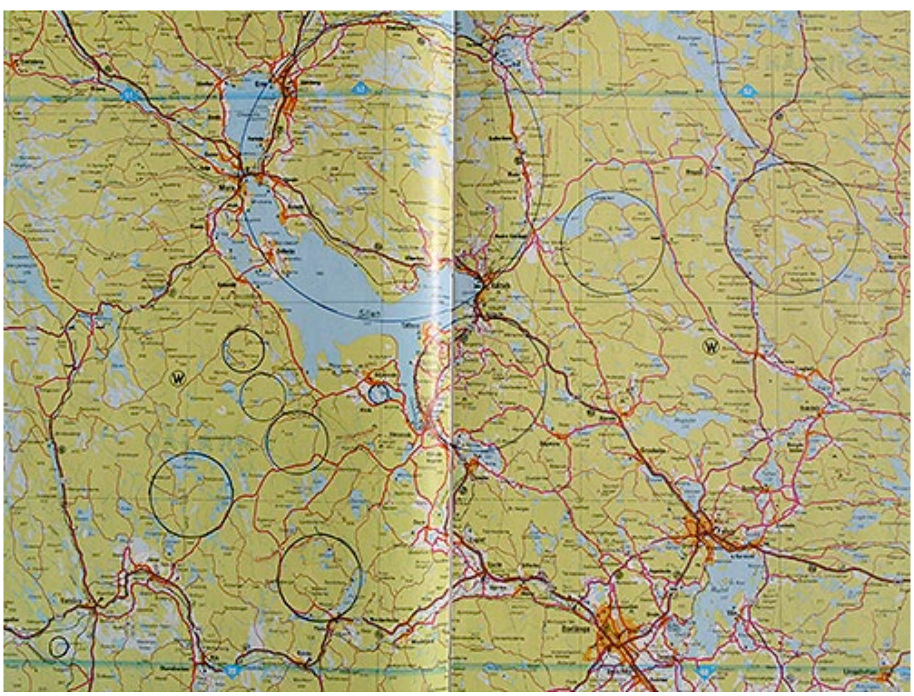

Fig. 0: Map of the region. Note the 10 blue rings south of Lake Siljan as sites of possible astroblemes. Grid size 25 x 25 km.

For the rings Stora Flaten-Snesen, Flosjön, Långsjön and Almosjön there exists strong evidence, that these really are astroblemes; within the supposed Långsjö-astrobleme there exist an active quarry, in which pseudotachylites and shattered bedrock is seen. Due to a possible transport of rocks from the nearby Siljan astrobleme by ice sheets during the Holocene, the evidence for the proposed Vådsjö-astrobleme is not as strong. The large Leksand-Insjö ring structure will be commented upon later on in this report.

2. WHY SO MANY RINGS?

Falling asteroids create large impact structures. Asteroids were the raw material for the formation of a planet to be between Mars and Jupiter, which, however, never coagulated to a single body like the Earth. To the best of our knowledge they can be regarded as a collection of cosmic “sand” or dust from exploded supernovas. The asteroids are large, but not large enough so that their own gravity should have compressed them to make them melt through; this limit occurs at about 1/10000 of the mass of the Earth, still at a formidable $5 \cdot 10^{20}$ kg.

When entering the atmosphere of the Earth at cosmic speed (≥ 11km/s) these bodies easily break up into pieces, which have the same speed and reach the surface of the Earth nearby. The probability that these ten bodies - lying so near by - are belonging to different falls is negligible. Since several of the supposed impacts – particularly the smaller ones – lie SW of the Siljan-astrobleme, we suppose, that the original meteorite approached the target from the SW.

The energy dissipated by a fall is $(1/2) \cdot mv^2$. We neither know the mass, nor the velocity of an object; however, we can make a relative estimate of the total mass of the approaching asteroid in relation to the (unknown) mass of the Lake Siljan impact.

At the same speed of all the objects it is reasonable to assume, that the mass of the excavated volume of rock $a \cdot r^3$ is proportional to the mass of the colliding object (r = radius of the astrobleme, in km). The calculation indicates, that for the Lake Siljan astrobleme we obtain for $a \cdot r^3 = a \cdot 8490$ and for the sum of all the other ten supposed astroblemes $a \cdot r^3 = a \cdot 2061$. Thus the mass of the Siljan astrobleme still is more than 4 times larger than the added mass of all the other supposed astroblemes.

3. BEDROCK OF THE TARGET REGION

The present surface bedrock is as follows: The central part of the Siljan uplift and of all astroblemes to the west of Siljan and of the Ljugaren region consist of younger serorogenic granites.

Leksands and Balungen astroblemes: Serorogenic granites and leptites (metamorphosed ashes from volcanic eruptions 1700 million years ago).

At the time of the "fall" an Ordovician carbonate layer covered the present bedrock, overlain by an unknown thickness of Silurian and soft Devonian sediments*.* This carbonate can be found here and there as inclusions in remobilised granite. Currently this carbonate sheet is eroded away with the exception of xenolithes, preserved in the ring dike of the Siljan-astrobleme under "fallback" breccia.

The impact of the Siljan meteorite occurred 377 milj. years ago on Devonian sediments. Below these Silurian and Ordovician sediments have been deposited. The thickness of the lowest layer – from Ordovicium - has by prof. Thurslund been estimated to 130 m; in total the whole stack of sediments must have been at least 200 m thick, probably much more. Thus the rim of the Siljan impact crater mainly consisted of soft sediments that to day are gone. Also the undamaged layers (outside the impact area) have up to date disappeared.

The conclusion of this statement is that we today are looking on a deep level of the crater, probably at its deepest point, where large quantities of melt have collected.

4. EFFECT OF IMPACTS ON SURFACES

The falling meteorite has very many effects on the at that time existing bedrock, which help us to identify a site as an astrobleme. However, there is one overall effect, which should be discussed on its own right.

During the impact, shock pressures of >100 GPa = 10^6 bar and temperatures >3000°C are generated, the latter mainly due to adiabatic compression /2/. This is the same effect as compressing air in a bike pump. When compressed, an ideal body is heated – but also cooled, when decompressed. Unfortunately bedrock is not an ideal body: It is heated by adiabatic compression (a reversible process), but also by friction between blocks of rock, sliding along one another. During this process heat is produced, too, but not in a reversible way: This heat stays within the rock and is relieved by conduction, only. This latter is a slow process.

Assume a cylinder of granite, with a diameter and height of 1 km, which had been heated to 1000°C right through. The cylinder perimeter is artificially held at 0°C at all time. Still after 580 years a central spherical part of 250 m diameter will be at >800°C /3/. The boundary conditions used here are completely artificial; at more reasonable boundary conditions (determined by an in time decreasing heat flux at the perimeter) the cylinder will cool much more slowly. High temperatures near 1000°C will prevail for ten thousands of years, which implies, that there is plenty of time at high temperature in a water saturated environment to form new minerals and new rocks from the debris of old ones. This author has found 5 cm large euhedral microcline crystals in reconstructed granite in the supposed Leksand astrobleme. In the original granite the microclines are ahedral and only some millimetres large.

5. METHODS OF FINDING SITES OF EVIDENCE

The topography often gives the first hint for the presence of an astrobleme. Lakes are not straight, but they appear as a boudin following the isohypses on the map, which latter often perpetuate the curved form of the lake. In the Flosjö astrobleme the lakes (two in series) and a dry valley encircle the astrobleme by about 220 degree.

In a forested landscape like Dalecarlia there is plenty of boulders in the forests. However, often they are heavily pitted or weathered and/or covered by moss and lichen. Thus it is hard to see, what is below the cover of the weathered surface and plant cover. In this case it is easier to check amelioration cairns in the fields. There the farmers have collected boulders discovered during ploughing and you get some feeling for the relative occurrence of the samples, you are looking for.

At granite sites the carbonate-preferring hepatica does not occur. If you nevertheless find hepatica and other carbonate-preferring plants, it is a good sign for the presence of carbonate, which in Dalecarlia means, that boulders, containing carbonate, have been cast there by the impact or later transported there by ice from a nearby astrobleme.

"Look for impact-related samples in gravel pits and in quarries, too." The Flosjö-astrobleme has been found by this method.

6. RECOGNITION OF ASTROBLEMES

Astroblemes are disclosed by the physical and chemical traces of the impact. In the case of the Dalecarlia astroblemes we have to consider that the meteorites have fallen upon a ground consisting of carbonate, which may have given rise to particular reconstructed minerals in the debris. In the following a collection of identification features is given:

6.1 Ring-shaped trenches often filled with lakes.

6.2 Shatter cones: Conical striae on broken pieces of the basement rock, emerging from the apex of the cone, length up to 0,5 m.

6.3 Within the crater there exists large tilted sheet ridges of the basement rock, with dimensions in the range 100 to 200 m along the cliff and 30 m above present ground, dip of sheet 20 to 80 degree.

6.4 Microscopic damage to grains of quartz and feldspar (PDF = Planar Deformation Structures) /2/. Micromounts and the petrographic microscope are needed for inspection.

6.5 Particularly for the Dalecarlian astroblemes: Large fields (0,5 km^2) of boulders of local shattered bedrock, not transported by the Holocene ice, not rounded. These fields are shown in the local topographic map. It is believed, that during the impact the granite cracked at more distant positions; however, these cracks have been cured later on. During the recent ice age these cracks broke up again; the blocks are lying more or less in situ.

6.6 Particularly for the Dalecarlian astroblemes: Mechanical inclusions of Ordovician carbonate (isolated grains up to 3 cm width) within from shattered bedrock reconstructed granite (Note: These inclusions are not later fillings of pre-existing cracks!)

6.7 Particularly for the Dalecarlian astroblemes, within pure granite areas: Boulders, containing fragments of previous rocks and glasses, obviously established as sediments in water and later deformed by mudslides.

6.8 Solidified mud, containing fragments of the previous bedrock.

6.9 Intensively shattered bedrock (shattered in all dimensions), cured by quartz-impregnation.

6.10 Shattered and reconstructed bedrock with large (up to 5 cm) euhedral or anhedral microcline crystals. These are dark-red, like in mylonites. Note: The crystals do not contain perthite.

6.11 Impact-melt breccias: They consist of a melt matrix, containing damaged fragments of the target rock. Definition by /2/.

6.12 Suevite: Polymict breccias with a clastic matrix, containing lithic and mineral clasts and cogenic impact melt fragments. Definition by /2/.

6.13 Boulders of granite of low strength and heavy weathering, not found in solid rock. These seem to be fragments of reconstructed rock.

6.14 High-pressure polymorphs of quartz (coesite and stishovite) in the debris, mainly in suevite. Micromounts and the petrographic microscope are needed for inspection.

6.15 Pseudotachylites: These are thin sheets of melt (normal thickness 1 mm, but up to 10 mm) between blocks of rock, which during the instant of impact have sledded along one another, definition by /2/, or are cracks. However, here it is not obvious, whether the melt has been created locally by friction or has been intruded in from a distant source. Since we have to assume, that the bedrock near the centre of an impact for long time (hundreds of years) has been at a very high temperature, melts could propagate far away from their source without solidifying. These thin sheets do not have fragments of the bedrock, but show gas bubbles. Pressed-in melt of distant origin often shows branching into minor cracks; these very thin branches often fade out. The rock-units on the upper and lower side normally are not displaced towards one another.

In contrary tachylites from gliding of the upper block along the lower block form a thin brown sheet without branching. Sometimes the lateral displacement between these two blocks can be seen. This type of gliding is a slow process: Even if within the gliding plane some heat is generated, its rate is so low, that the rock volume around the gliding plane remains cold.

6.16 Boulders of the type 6.11 and 6.12, which give the impression to have been metamorphosed by steam or hot water. Some of their constituents are transformed into clay minerals. This resembles dark basic lava near fumaroles, which is transformed to kaolin (Furnas, Island of Sao Miguel, Azores).

6.17 Since large meteorites (kilometre in size diameter) vaporize during the instant of impact they may spread their mater over large distances, sometimes around half the Earth. If they contain odd elements like those of the platinum group (PGE), these may be used to ascertain the fact of an impact. However, not all meteorites contain such odd elements.

6.18 Applicable not for all, but certainly for the Dalecarlian astroblemes: There sometimes carbonate-preferring plants can be found in a pure granite environment, where they should not occur. The reason for this is: Carbonate from the Ordovician occurs mechanically included in reconstructed granite or conveyed there by the Holocene ice.

Numerous textures, structures and formations of different rocks have been found in many astroblemes; for this reason this author would like to suggest the following generic subdivision, exceeding that from /2/:

1. Primary impactites (melts formed during the impact of the impacting body and/or from local bedrock)

1.1 Impact-melt breccias
1.2 Suevites
1.3 Pseudotachylites
1.4 Reconstructed granite with bulbs of glass or melt.

2. Secondary impactites (these are formed after the impact)

2.1 Quartz-cured original crushed rock
2.2 New rock, mainly consisting of coloured quartz.
2.3 In water settled material, possibly sub aquatic slumps, which has been metamorphosed
2.4 Hardened slurry of mainly carbonate dust, converted to carbonate-siliceous rock
2.5 Mylonites, similar to red-brown porphyries, consisting of potassium feldspar, free from the glass phase of a porphyry.

The “best” samples consist of intergrown microcline crystals, without any free quartz (=syenites), see 7.8.

2.6 Reconstructed granite

The rock type 2.3 has to be explained: We can assume, that at the site of the impact there was plenty of water present. Large amount of water, powdered rock and rock fragments have been cast out of the new crater. Immediately afterwards, together with the sediments, the water flowed down to sites at lower level. Subsequently later, slumps in the instable sediment formed rocks, similar to those found in sub aquatic slumps. This type of rock has been found in the Lake Flosjön-astrobleme.

7. DESCRIPTION OF THE INDIVIDUAL ASTROBLEMES

7.1 THE LAKE SILJAN-ASTROBLEME

To obtain tokens for the recognition of all the other minor astroblemes we first must discuss the finds from the Siljan-astrobleme. If these are accepted as consequences of a meteorite impact, similar rocks and features at other places have to be accepted as a proof of an astrobleme for that site, too. Here we have to be aware of the fact, that blocks of Siljan-material may have been transported by Holocene ice to the present site.

During exploration for Natural Gas twenty years ago in the centre of the Siljan ring an outcrop has been discovered (Pos. A), consisting of the solidified impact-melt. Unfortunately this author does not know, who has made this discovery and if it is published. For this reason it is here unsuitable to mention the coordinates of that outcrop.

Fig. 1: Impact-melt breccia from (Pos. A).

In its most homogeneous part this rock resembles a dark-brown Dalecarlia-porphyry, which should have been overlooked, when found as a loose boulder in the till. Of course this outcrop should not be touched. However, there exist plenty of boulders of nearby origin in the local till. Some can be regarded as suevites 6.12, others as impact-melt breccias 6.11. In these latter, thermally and mechanically damaged granite is floating within the brown melt (sometimes glass is used for melt). Here we have a large difference to porphyry: Phenocrysts in porphyries are monomineralic; here the melt contains fragments of the target rock, consisting of several minerals (Fig. 1). This is the final proof that the Siljan ring is an astrobleme.


Fig. 2: Gliding in sheared granite (Pos. B).

At (Pos. B), a gravel pit on the road to the lake edge at Garsås, one can collect all types of impact-created rocks: Melt, completely crushed and reconstructed granite (Fig. 2), pseudotachylites in granite (Fig. 3) and an impact rock, metamorphosed by steam (Fig. 4a).

Fig. 3: Peudotachylites in sheared granite (Pos. B).

During the 1960:s the only evidence for the astrobleme hypothesis was the ring trench, shattered and tilted sheets of carbonate rock from Ordovician and shatter cones in the centre of the structure. Since then it has been shown, that shatter cones are not at all so rare, but can be found here and there, e.g. in the till at the edge of the Lake Siljan near the village Stumsnäs, there at a stone pier (Pos. D). Some 100 m NE of that point there is an outcrop on the shoreline (visible only at low water level), consisting of crushed granite in carbonate-silicate slurry.

Fig. 4a: Weathered melt, probably exposed to steam (Pos. B).

In addition, there is a new site of crushed and quartz-annealed granite at the Lake Siljan shore, belonging to the village Garsås, (Pos. C). Annealing of meteorite-damage by quartz differs from that of structural movement, since in the first case the boulders are criss-crossed by the quartz-veins, whence in the other case there is only one (1) direction of quartz annealing. At (Pos. C) there are so many boulders that the outcrop has to be close; best it is seen at low-level water. At this site one can find:

- Completely smashed granite
- A reconstructed rock, consisting of quartz
- Quartz formed in situ with asphaltenes in cracks
- Shatter cones

In reference /4/ Liljequist gives a further compilation of structures/textures, created by the impact of a larger meteorite.

Near (Pos. C) is a pier at (Pos. Aq), built up by boulders, dragged from the nearby waters. Here boulders up to 500 kg of pure white quartz are seen, showing an unusual rectangular cleavage. Since in the local bedrock pegmatites are not known, the origin of the quartz and their cleavage is not known.

Another, easily accessible site is the shore of Lake Siljan at the church of Rättvik, (Pos. Ar). There a cross is raised on an outcrop of a preserved so called Silurian sandstone. In fact, the outcrop has been formed during the

impact of the meteorite during Lower Devon. Details of this interpretation will be given in chapter 8: Discussion: Hypothetical interpretation of the origin of the Orsa sandstone.
The shore below the cemetery (accessible at low-water, only) contains a lot of other impact-damaged rocks, too. Mainly they consist of fine-grained calcite like marble, of white, reddish or greenish colour. However, they are not primary sediment (layered Ordovician limestone), but consist of sintered carbonate dust, without traces of fossils or other bedding texture. This is clearly seen by the presence of quartz grains in the weathered carbonate surface. The visible grains are lifted above the surface of the limestone by corrosion of the latter, have often the shape of a lens. New quartz-grains (from a deeper level) can easily be disclosed by etching. Certainly this mixture of quartz and calcite is due to the blasting of the pulverized bedrock during the seconds of impact. Primary calcareous sediment at sea bottom is always free from visible quartz- and other grains.
A similar bolder of reconstructed calcite is exposed outside the public library at Rättvik. In this paper the term 'reconstructed rock' is used for similar formations. See Fig. 4b.

Fig. 4b: Reconstructed calcite from (Pos. Ar). Real lengths of view is 3,5 cm.

Here this author would like to add additional information on particular sites according to:

Ring-shaped trenches, waterfilled and/or dry (6.1):

- Lake Flosjö

Tilted plates (6.3):

- In the Siljan astrobleme: Carbonate quarries at Amtjärn, Skålberg and Osmundsberg
- In the Leksands astrobleme: Granite at Käringberget and several similar sheets north of Käringberget
- In the Almo astrobleme: The island Storön in the Almo lake.

Note: Tilted plates not necessarily occur at the rim of the crater, only. For example, there is a limestone quarry at (Pos. An), with the former horizontal carbonate beds now upraised to vertical position. This site is only 12 km distant from the centre of the Lake Siljan-astrobleme.

There is no report from the Siljan astrobleme of large fields of local giant boulders (6.5) in the moraine; however, these are found in the Stora Flaten-, the Flosjön-, the Hummelsjö- and the Rågsveden-astrobleme.

7.2 THE LAKE STORA FLATEN-ASTROBLEME

During the spring 2005 this author has found evidence for that the ring north of the village Dala-Järna, including the lakes Stora Flaten and Stora Snesen, could be an astrobleme. This ring has a diameter of 10,5 km, measured between the outer rims of the ring dike. Its centre is at (Pos. E). To reach interesting sites take the forest road between the lakes Stora Snesen and Åskaken, which starts from the public road between Leksand and Dala-Järna at (Pos. F) and reaches after 3 km the south end of the minor lake Långtjärn. East of the road you are within a large area, where one or two years ago the forest has been cut down and the undergrowth burned away. The fire has removed all brush and cleaned the boulders. Here again it is easy to find similar samples as in the Lake Siljan-astrobleme like:

- Shattered granite, cured by criss-cross of later quartz veins (Fig. 5)
- Impact-melt breccias, within which fragments of granite float in the melt (Fig. 6)
- Boulders, resembling pyroclasts (Fig.7)
- Shatter cones in moraine boulders

Fig. 5: Crushed granite with innumerable cracks, cured by quartz filling.

Fig. 6: Impact-melt breccias. The elongated sample is from (Pos. G), the round one from the centre of the Siljan-astrobleme.

Fig. 7: The sample resembles sintered ‘volcanic’ ash (Pos. G).

At (Pos. G), near a dead birch, there lie two boulders. One of them is very similar to the impact-melt breccias from the Siljan region (Fig. 6). The elongated sample is from the Stora Flaten-astrobleme, the rounder from the Siljan region at (Pos. A). The other boulder from the dead birch (Fig. 8a) has another character, not found in the Siljan-region. It resembles a pyroclast like one from the Azores or from south of Rome. It consists of small granite fragments in a yellow ash and probably is a suevite. Please leave these boulders untouched as examples for other visitors. There is no problem to find similar samples on the burned spot.

Fig. 8a shows a block found in a small gravel pit north of the northern end of Lake Långtjärn (Pos. H). The melt in this block is darker then that from the Siljan region. The white and grey inclusions in this sample are calcite (Note: This is not a late filling of cracks by a solution, but mechanically agglomerated calcite grains). In other samples, not shown here, there is more calcite. How can calcite enter a “granite”, if not mechanically?

Fig. 8a: The sample contains a darker melt than that from Lake Siljan and some agglomerated calcite (Pos. H).

In the same pit there is a larger – not transportable - boulder with quartz curing and dark glass. Note that the everywhere present boulders of the local granite are quite different from our astrobleme samples.

Another site for finds of impactites is a recently built forest road, which starts at (Pos. I) and leads to the west. At the end of that road (Pos. J) you can find impact-melt breccias. One can speculate, why impactites have not been found within the ring yet, but outside the ring at Långtjärn. There are some low hills, may be of 30 m height above lake level, to day completely covered by till. We may assume, that these hills contain a core of impactite-material, from which the small boulders are derived.

Some readers may suggest, that the samples found at the Lake Långtjärn may have come there by icedrift from the Siljan-ring. This cannot be the case: The ice flow direction from the centre of the Siljan astrobleme passes Långtjärn about 40 km east. Besides, the impactites are very fragile and could never stand such a long journey.

Lake Stora Flaten forms the northern branch of this supposed astrobleme and Lake Stora Snesen its eastern part. Inside this ring, but also outside, there are extended fields of large local moraine boulders. These are very little worked by transport. Most of the boulders are several m^3 large; the largest one at is about 50 m^3 large. We believe, that the bedrock has been broken up during the impact; the fractures certainly have been annealed by quartz. 377 million years later, under the Holocene ice cover, the old fractures have broken up again and the boulders form these large fields, see (Pos. K).

Another site for finds from this astrobleme is an old gravel pit at the northern end of Lake St.Baggbod-Öradstjärn at (Pos. L). This place is south of the Lake Stora Flaten astrobleme; most probably the impact specimen have come there transported by ice. A further site is a gravel pit at (Pos. As). There reconstructed granite, sealed by a dark melt, is to be found.

At the northern shore of Lake Stor-Flaten a very interesting observation has been made. The lake has quite clean water, somewhat dyed by humus, but low in nutritive salts. Also its level varies due to damming. This prevents the establishment of algae on stones at the water's edge. Between (Pos. Av) and (Pos. Aw) on the shore almost every stone/bolder has been affected by the impact. However, most interesting is a rather rich occurrence of layered flint. Real flint is in Dalecarlia a very rare mineral (chalcedony), is much rarer than e.g. the rare alkaline volcanic rock tinguaite. Where from comes layered flint? The answer must be: From Ordovician or later up to Devonian limestones. These contain radiolaria, the quartz of which concentrates by metamorphosis in bands within the limestone beds. This certainly happened in the whole sedimentation basin, but has been preserved, only, under the ashes of an astrobleme. The flint is white, greenish or peach.

Fig. 8b: Boulder consisisting of flintpieces, wrapped in red-brown melt. Part of the Inclusions is flint

At (Pos. Aw) a bolder has been found – see Fig. 8b – that is a breccia of flint, only, glued together by a red-brown melt. Several similar boulders have been found at other astroblemes and confused this writer: One near (Pos. G), one at (Pos. V) and one near (Pos. Ax). The sample from (Pos. Aw) shows very clearly, that a hot melt has been pressed into a loose heap of shattered flint.
The objects shown in Fig. 8b, Fig. 17 and Fig. 18 could be formed like Melosh /11/ indicates in his figure 8.2.a). However, to be honest, an other mode should be mentioned, too. Lundquist and Svedlund /12/ have studied breccia and other rocks in northern Dalarna. These rocks have been formed in the interface between the Dala porphyries and the covering Dala sandstones. Look particularly for their figure 65. The key question is, what the brown matrix consists of: Vitrified glass or sintered sand?

Considering the relative positions of the lakes Mellan-Flaten, Siksjön, Skålsjön and Stora Snesen these lakes form a quadrant of a circle with its centre at Flatnäsberget (142570E/672525N). This could be the centre of the impact, if this in fact was vertical; the named lakes could be the outer rim of a complex crater. From this centre 2.6 km (as the crow flies) to NE there is a large gravel pit at position (142793E/622686N), opened to supply material for a new forest road.

Here we find very many samples of local rock, which have been heavily affected by the impact: Almost all consist of reconstructed rock. A tentative explanation could be: During the impact the rock within the central regions of the astrobleme has been pulverized and blown up, together with the vaporized residues of the meteorite. At the time of the impact this rock has been Silurian slate, Ordovician carbonate and Precambrian base rock. This mixture fell back, its components started to react with one another during the following millions of years. Crystals of quarts and feldspar grew in the mixture, could displace the soft calcite and attained free forms at their surface. In recent times, when the rock has been broken up by land ice, the blocks have been exposed to weathering and the carbonate has been dissolved out of these stones.

To day their surface is extremely rough, showing the welldevelloped faces of the ingoing crystals and a very visible porosity after exsolved carbonate. The following figures cannot really show how large this porosity in fact is. A drop of water immediately disappears into the sample. See Fig. 8c and 8d.

Fig. 8c: Highly porous sample of reconstructed granite.

Fig. 8d: Highly porous sample of reconstructed granite.

Fig. 8e shows another interesting thing: Due to the fact that this sample is practically free from visible quarts the sample should to day be called a reconstructed syenite. It consists of mainly microcline, some plagioclase and plenty of black chlorite. Chlorite contains a lot of iron, which is not normal constituent of granites, except as hornblende. However, an iron meteorite could very well supply the needed iron atoms. Note in the lower part of the figure a dyed quarts dike; this is a later event in the history of this stone.

Fig. 8e: Consolidated “fall-out” from particle-cloude.

A third interesting sample originates from position (142871E/672568N), here shown as Fig. 8f. Here the ingoing mineral grains have no other generic relation to one another than that they are an air-borne sediment from the cloud of blown-up fragments.

Fig. 8f: Reconstructed syenite with dark chlorite.

7.3 THE LAKE FLOSJÖN ASTROBLEME

Studying the map sheet 13E SO Vansbro more carefully one would discover, that lake Flosjön is part of a ring trench with a perimeter of 220°, with its centre at (Pos. M) and a radius of 5 km. In the east this ring passes the Harpick-island in the Lake Flosjön and the hill Tutberget on that island (Pos. R). Tutberget is nothing else than a tilted sheet, similar to Käringberget in the town of Leksand. It rises about 27 m above the level of the lake, with strike 20°E and a dip of 60 to 80°E. Another indication for an astrobleme is the accumulation of large local moraine boulders in the centre of the ring at a location named Trolldalen and at other locations near the ring.

With the previous knowledge from the Stora Flaten-astrobleme this author has investigated a nearby location outside of the ring, i.e. the foot of the hill Bodberget near the Alpine pasture Forsbodarna (Pos. N). According to rumors hepatica should grow there. Indeed, it was found there in a granite region on a saddle surface between Bodberget and Forsbodarna. In the amelioration cairns - besides normal granite - boulders were found, very similar to impact-melt breccias. These contained isolated clusters of free calcium carbonate (no late filling of cracks), which explains the occurrence of hepatica and other carbonate-preferring plants (Fig. 9).

Recently a new forest road has been built from the nearby road terminating at Forsbodarna; this new road starts about 400 m north of the end of the Forsbodarna road and leads to the saddle. Along this new road and at the saddle surface several further amelioration cairns have been detected, which contains hundreds of boulders that are damaged by an impact. Of one of these boulders a thin slide for microscopic examination was prepared. Even there crushed grains of individual minerals are seen; other minerals fill the crevices.

Fig. 9: Plenty of dark glass in this sample. The white dots are calcite and a calcium-silicate (Pos. N).

Along a recently built forest road N of the summit of Bodberget in the valley of the brook Nordanbergsängs-bäcken (Pos. O), there are further boulders with cracks, filled with pseudotachylite. However, the richest site for finds is quite near at (Pos. P), which is an area ploughed some years ago, where the trees have been cut down. It is about 100 m W of the turning for Forsbodarna. There almost every block or boulder is affected by an impact; mostly you will find secondary impactites of type 2.3 of our classification. Fine-grained material seems to have been collected at a particular site and later sledded downhill, forming a rock, similar to subaquatic turbidities, see Fig. 10, 11 and 12.


Fig. 10: Nice sample of water-transported secondary impactite (Pos. P).


Fig. 11: Weathered and water-transported fine stuff (Pos. P).

Fig. 12: Layer of tumbled granite pieces on fine stuff (Pos. P). On downside weathered melt.

Likewise there is a dark red metamorphic rock, consisting mainly of red microcline and small amounts of epidote, almost free from quartz, Fig. 13. Despite this rock is similar to red porphyry, it is free from a glass phase. Similar red microcline is formed in fracture zones from the stone powder. Here and there on the sites there are boulders of the similar Garberg granite or Garberg porphyry from a site about 75 km NNW, and for this reason the red metamorphic rock could be a fraction from Garberg. However, this red metamorphic rock is found at all sites of impactites, only, which makes the Garberg origin somewhat questionable. One can imagine that a hot-water fluid had leached powdered granite. The fluid has removed all quartz and left behind the potash-feldspar powder, which later on metamorphosed to the red rock.

Fig. 13: Very dark red microcline like that formed from mylonite in a slip cracks. The dark dots are rounded grains of quartz.

Recently (in 2010) a new area nearby has been ploughed and thus has disclosed plenty of impactgenerated samples. It is at the previously mentioned turning for Forsbodarna, but south of this turning. There every second stone or boulder is affected by the impact. Fig. 13a shows a quarts-free sintered ash or sediment with an overcrossing wide quartsvein. Fig. 13b shows the red brown feldspar-residue. This ploughed field is an unlimited supply of impact-generated samples.

Fig. 13a: Recrystallised ’ashes’ from Lake Flosjön-astrobleme

Fig. 13b: Microcline-rich ’ashes’ from Lake Flosjön-astrobleme

A further location for finds is the centre of the Lake Flosjö-astrobleme at Trolldalen. There, in addition to giant scale boulders, at (Pos. Q) an old gravel pit with heaps of discarded stones and boulders occurs. This material – as everywhere in gravel pits - is water-transported to the very site, therefore not typical for the bedrock just below. There exist stones of the local granite, which evidently have been crushed to debris, but cured by glass to a new resilient stone, se Fig. 14 and 15. The glass content varies between 10 to 90%. The rock is hard, not equally disintegrated as the impacted granite from the Lake Siljan astrobleme. At this site a stone was found containing two balls of glass, of the size of a hen's egg, see Fig. 16a. Before the impact, there are no cavities in the granite, which could be filled with the liquid glass. Thus the granite during the impact must have been disintegrated to grains, around which the glass has been pressed in; subsequently this mass has solidified to the resilient rock, we find to day.

At the same site (Pos. Q) another stone has been found, which – after deliberate crushing – showed grains of granite floating in a dark-brown melt, see Fig. 16b. There are white grains in the mixture, too, which proved to be calcite. How can calcite enter reconstructed "granite", if not mechanically after the original granite has been shattered to small fragments? This site is near the centre of the impact: Its force there has acted vertically downwards and had only a small component of sheer aside, which is found in more peripheral locations. This could be the explanation for the resilient glass-impregnated granite.

Fig. 14: Sawed plate of restructured granite from Trolldalarna (Pos. Q). The dark filling is glass; these fillings are interconnected.

Fig. 15: Glass in hard rock from Trolldalarna (Pos. Q).

Fig. 16a: Egg-size drops of glass on reconstructed granite, Trolldalarna (Pos. Q).

Fig. 16b: Mechanical calcite inclusions in reconstructed granite, Trolldalarna (Pos. Q).

Recently (August 2010) at (Pos. Q) several large blocks of shattered granite, cured by a melt, containing large inclusions of that melt have been found, see Fig. 16c. These samples are comparable with the bests from the Siljan-astrobleme.

Fig. 16c: Sample of reconstructed granite with solid melt

Another site of rich occurrence~~s~~ is a slope at (Pos. V). There and even at (Pos. G) two very strange blocks have been found; without doubt these are conglomerates. In the Siljan-area there exist conglomerates at at least two locations: At Lake Djurssön and at the village Söderås, 2 km S of Rättvik. These conglomerates are ordinary conglomerates, containing rounded stones of different nature in sandy sediment as matrix.

The conglomerate from (Pos. V and G) is completely different from ordinary conglomerates: The round inclusions consist of an amorphous material like flint, but contain round cavities like gas-bubbles. These are partly filled with crystals. One gets the impression of a solidified, devitrified glass with gas inclusions, Fig. 17 and 18. Fig. 18 is the rear side of the right sample in Fig. 17. The matrix of the conglomerate is the brown stuff like in Fig. 4a. Could this be some late agglomeration of original impactite material? Ordinary conglomerates do not contain balls of amorphous material with gas bubbles!

Fig. 17: Conglomerate consisting of balls of flint-like stuff in a matrix similar to impact-melt.

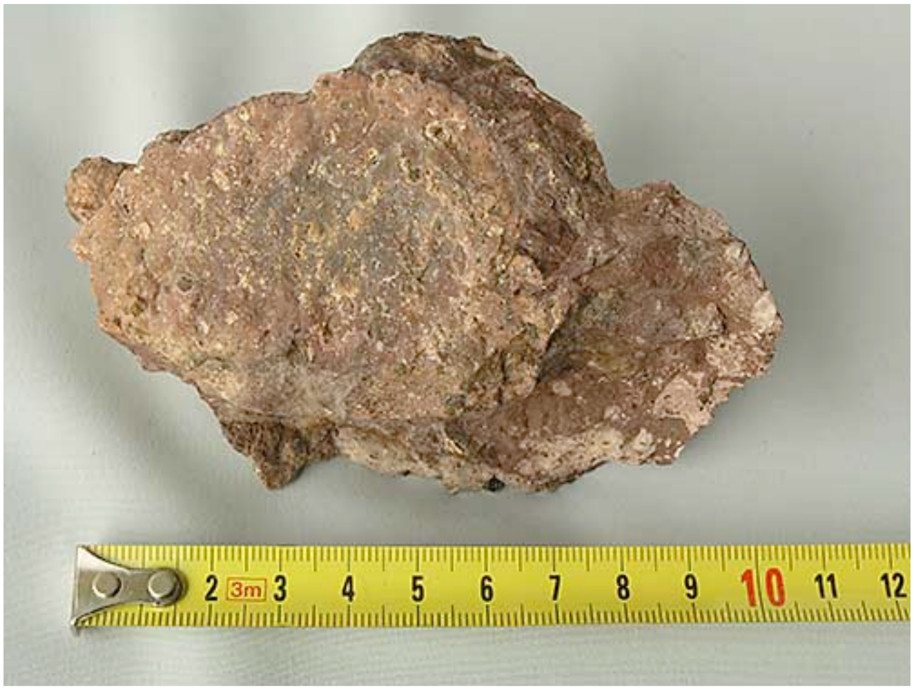

Fig. 18: Rear side of right-hand sample in Fig. 17 showing the flint-like stuff.

Two kilometers south of (Pos. V) there is another one (Pos. W) within a small, protected area – Björberget - that is extremely rich in hepatica. This site is so far away from the Lake Siljan astrobleme that in this granite a local source of carbonate must exist, either a residue of the original cover of carbonate or boulders of carbonate, transported there. Transport from the Siljan-astrobleme is extremely improbable. A thick cover of soil makes the excavation difficult. Pseudotachylites are found, too, in very fine-grained granite along a forest road at (Pos. Ao).

All these sites and occurrences, also the tilted granite sheet on the Harpick-island, makes me completely convinced of the astrobleme origin for this ring.

7.4 THE LAKE LÅNGSJÖ-ASTROBLEME

The Lake Långsjön-astrobleme has its centre at (Pos. X) and a radius of 4,25 km. Roughly 180°of its perimeter consists of the lake or of lowland with parallel isohypses. The whole area is covered by forest; for this reason searching for impactites is very difficult.

However, about 1 km inside the perimeter there is a quarry at (Pos. Aa), which is very rich of pseudotachylites (here thin layers of a brown melt or a brown precipitate between blocks of bedrock, that have sledded on one another), of pieces of shatter cones, of now exposed surfaces, where the sliding can be seen and of quartz-cured crushed granite, see Fig. 19a. Note the melt phase between the two quartz veins. Evidently later the blocks on opposing sided of the tachylite have separated somewhat, allowing quartz-saturated water to penetrate the crack. Tectonic movement is far too slow to generate so much cracks and glass and does not generate crushed granite, which later on is sealed together by quartz solutions in water.


Fig. 19a: A melt phase between the two quartz veins.

During blasting in the quarry the rock sometimes separated at old cracks, thus freeing the tachylite. This is normally 1 mm thick, can reach up to 5 mm. In such melt fillings small grains of other rocks are seen, indicating that this melt has been pressed in from a distant position. A prerequisite for this mode – distant transport – requires the rock to be hot, i.e. heated by adiabatic compression. See Fig. 19a, 19b and 19c. At the entrance to the quarry there are two boulders to prevent the access. Check these: They contain plenty of thin dikes with brown melt.

Somebody might suggest, that the ‘pseudotachylites’ are due to simple filling of cracks by mineral-rich water. This cannot be the case, since water never would leave gas bubbles in the ‘sediment’. Recently (autumn 2009) new blasting in this quarry has taken place.

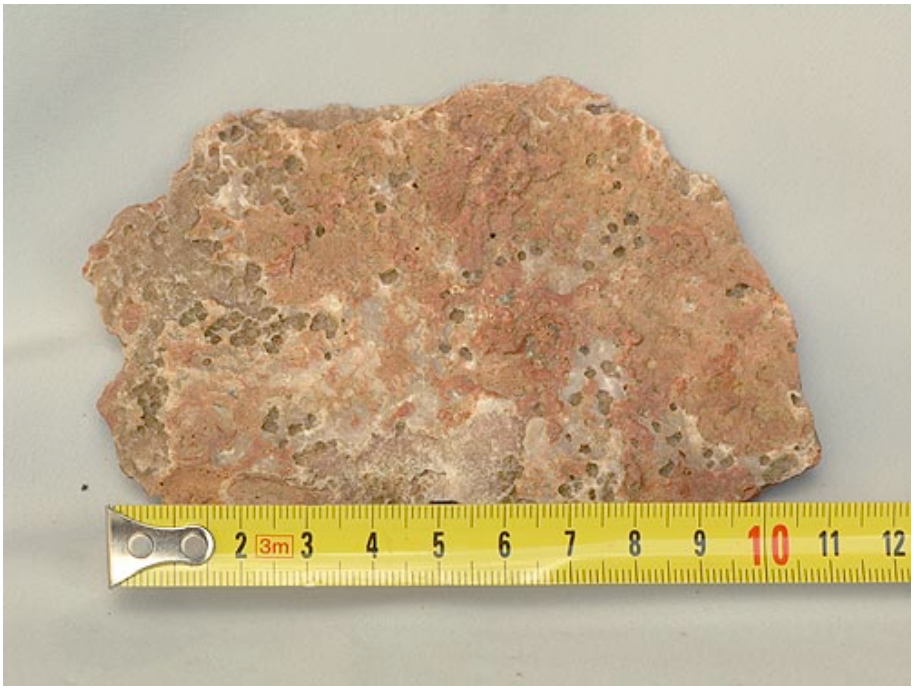

Fig. 19b: Layer of pseudotachylite, quartz-rich side, 5 mm thick.

Fig. 19c: Same pseudotachylite as in figure 19b, the rear side rich in melt.

Fig. 19d: Two pseudotachylites about 5 mm thick.

There exists much evidence for that the bedrock in the quarry has been affected by an impact. This could be an impact by itself (the Långsjö-astrobleme) or due to the damage done by the Siljan-astrobleme.

Concerning this latter hypothesis we have to look for positions of the same damage at similar distance from the Siljan-astrobleme. Disregarding the damage to the bedrock and its tilting inside the ring, there is evidence of tilting in the exposition Kårgärdet, about 1,5 km NE of the Orsa railway station. Here the Ordovician limestones and the local porphyry are raised up to 70°; the distance to the centre of the Siljan-astrobleme is 18,7 km. The next expositions to the east – the limestone quarry Kallholn – is at the same distance, but practically not affected. The last exposition at Kallmora is at a distance from the centre of 19,2 km. There, a fine-grained sandstone (Orsa-sandstone) from upper Silurian, is not affected at all.

The quarry at the supposed Långsjö-astrobleme is so far as 37,5 km from the centre of the Siljan-astrobleme. If we cannot find additional sites of damage at a similar distance due to the Siljan-astrobleme we have to assume, that the Långssjö impact is an astrobleme of its own. This in turn strengthens our hypothesis that several of the other investigated supposed astroblemes are in fact real astroblemes.

Within this supposed astrobleme there are two further sites of finds. The one is a forest road north of Gäddtjärn with coordinates according to (Pos. At). There in the sand of the road filling stones affected by an astrobleme are found. Near the road very many giant boulders are seen.

The other site is a gravel pit (Pos. Au), which most probably has furnished the gravel to above road. There are so many boulders in the gravel, so they had to be blasted. These rocks look like reconstructed granite with constituents, not normally seen in granite.

A further site inside the Långsjön-astrobleme is at (Pos. Bd). This position is that of the forest road nearby. West of this road forest ploughing has taken place and unearthed many stones and boulders, which have been affected by an impact. One of the boulders is a breccia, welded together by a brown melt.

7.5. THE LAKE VÅDSJÖ-ISRAELSSJÖ-ASTROBLEME

The centre of this supposed astrobleme is at 13 km west of the church at Siljansnäs at (Pos. S); its radius is 3 km. During the first inspection this author reacted upon the rich vegetation along the small river Långsån, which indicates carbonate. This could be due to local residues of the former carbonate cover or material from the nearby Siljan-astrobleme, conveyed there by the Holocene ice. At (Pos. T), in a gravel pit, a large fraction of the boulders is affected by an impact. Pure melt is rare, as shown in Fig. 20; Fig. 21 shows the cracked and quartz-cured rock. However, in a nearby large gravel pit at (Pos. U), about 3,5 km south of (Pos. T), impact-affected boulders are missing. Therefore those from (Pos. T) can be local.

Fig. 20: Layer of melt through granite. The thin white band is a late quartz impregnation along the old fracture zone (Pos. T).


Fig. 21: In all directions cracked and quartz-cured granite (Pos. T)

A further site for finds is a forest road, leaving a larger forest road at (Pos. Y) and climbing up to its end at 340 m height. Along this road impact-affected material can be found. One find is a block of brown coloured (former) quartz jelly, which contains silicified pieces of the stem of a crinoidea, Fig. 22.


Fig. 22: Silicified pieces of stems of a crinoidea in quartz-rich matrix.

Fig. 23: Metamorphosed melt (Pos. Z).

A further site of finding is a gravel pit at (Pos. Z), where only one interesting piece of a metamorphosed melt has been found, Fig. 23. This piece could originate from the Lake Siljan-astrobleme.

At Lake Vådsjön there starts a canal for water transport to a hydropower plant; it is cut out of the rock. May be, samples of the local rock could be found there. Up to now the nature of this ring is not completely clear.

7.6 THE SILJANSNÄS-ASTROBLEME

South of the village Siljansnäs there is a lake communicating with Lake Siljan. It is almost divided in two by an island; the western side of the lake is called Alviken, the eastern side Byviken. Around this lake there is a chain of hills. If it wouldn't be for the rich occurrence of carbonate-preferring plants one might have overlooked this supposed astrobleme and never investigated it. However, even this ring seems to be an astrobleme with radius 1,2 km. The evidence for this is the island, called Storön. This island is elongated, length about 2 km, heading 20°W, forms a large sheet with strike 20°W and dip 20°E. May be one would not react, would it not be for the cliff at its east side. This is about 30 m high and absolutely vertical, called Digerberget. Here we have a tilted sheet, like "Käringberget" inside the town of Leksand.

Fig. 24: Pseudotachylites at (Pos. Ab).

At (Pos. Ab), in an amelioration cairn, there are stones with undeniable traces of pseudotachylite, Fig. 24. A further site for finds is near the village Siljansnäs in an amelioration cairn (Pos. Ac).

Since the large Siljan astrobleme is too far away to tilt a sheet, we have to assume, that even the Siljansnäs-ring is an astrobleme. Boulders with impactite marks can have been transported here from the Siljan-astrobleme, but not the tilted sheet in the local lake.

7.7 THE LEKSAND-ASTROBLEME

From Lake Siljan there runs a narrow bay like an estuary to the town of Leksand. From the village Östanhol to Leksand this bay has a curved rim. Southwest of Leksand this depression in the terrain continues into the next Lake Insjön. During a late phase of the most recent Ice-age, when the level of Lake Siljan was about 8 m higher than to day, there was a continuous bay from Östanhol to the east end of the Lake Insjön. This corresponds to roughly 180° of the whole perimeter. This was the first indication, that there might exist a further astrobleme, here called the Leksand-astrobleme. Its centre is at (Pos. Ad) and the radius is 8,4 km.

The next indication is a series of tilted sheets in an area north of Leksand. The first and most impressing one is that within the town of Leksand, named Käringberget (Pos. Ae). The name is associated with the burning of witches in the 1670:s at that place. In fact, the place is unusual even from a geological point of view. From the former execution place (to day a parking lot) and 10 m to the west one reaches the brink of a formerly horizontal plate of granite, now dipping at 60°W and striking 30°W. The top of this plate is about 75 m above the level of the railway east of it, i.e. above the valley level; the foot of the plate disappears in moraine boulders, see Fig. 25.

Fig. 25: Tilted sheet of Käringberget, west side.

Another, similar tilted sheet, is at (Pos. Af), height about 25 m above surrounding ground. There are additional similar and minor cliffs north of Käringberget, all parallel to the supposed ring trough. It is hard to believe that these should have survived since the latest large folding epoch, which occurred during the Paleoproterozoikum. However, they could very well have been caused by a meteoric impact. Therefore searching for impactites started. At South Torrberg several such have been found in an amelioration cairn at (Pos. Ag), pseudotachylites and a reconstructed boulder with 5 cm large potash feldspar crystals. At North Torrberg there is a larger boulder in an amelioration cairn, containing many thin pseudotachylites (a brown melt), (Pos. Ah).

Another site is east of the former railway station Slättberg. There exists older granite, only. Parallel to the public road there is a forest machinery track. These vehicles have crushed the granite by their load; the fracture is often along former pseudotachylites. Here these are very thin, around 1 mm, filled with brown melt. This granite is local, no other (ice-transported) rocks exist (Pos. Ai). Therefore the tachylites also have to be local.

The most interesting place is a quarry near the road Rättvik-Falun at (Pos. Aj). It is situated on the rim of the supposed astrobleme. In this quarry for macadam all types of rock exist: Granite, a rock consisting mainly of coloured quartz and a black dike, to day consisting of chlorite slate (might have been black shales from the Ordovician Tretaspis layer). Also a few pseudotachylites occur, see Fig. 26. The distance to the centre of the Siljan-astrobleme is 25 km. The quartz is of a glassy variety, clear but dyed, hard and brittle like pegmatite. Pseudotachylites are few, probably because they have been destroyed later during their life. There is a brown rock, looks like porphyry, with inclusions of cm-large fragments of the chlorite slate. To this author it appears, that the "porphyry" is not at all porphyry, but consists of brown-dyed quartz, which has absorbed fragments of the chlorite slate, see Fig. 27.

Fig. 26: Pseudotachylites at (Pos. Aj).

Fig. 27: Brown dyed quartz with inclusions of chlorite slate (Pos. Aj).

Most probably we are looking here inside the bedrock on a portion, which had been very hot for thousands of years and percolated by steam. This has broken down remainders of feldspar and changed the Tretaspis layer to chlorite. The question is, if this is due to a local astrobleme (the Leksand-astrobleme), or to the nearby Lake Siljan-astrobleme. The distance from the quarry to the centre of the Siljan-astrobleme – as we define it – is 25 km.

The west side of the road between Sätra and Plintsberg is – due to its richness of hepatica, hazel and orchids - a Natural Park. The biological reason for this is a rich occurrence of calcite in the soil. However, solid calcite rock never has been found. Certainly the calcite originates from the Ordovicium and has been cast there from either the Siljan-astrobleme or the supposed Leksand-astrobleme. Several pieces of suevit and one piece of calcite have been found.

In summary: The sheets of rock, tilted near Leksand and the ring dike west of Leksand point towards an astrobleme of is own; the rocks in the above named quarry point very strongly on heat effects from an astrobleme, but not from which. The quarry is in continuous operation: Therefore the exposed rocks continuously change.

7.8 THE SUPPOSED LAKE LJUGAREN-ASTROBLEME

On the topographic map 14F SO Rättvik the lakes Dådran and Ljugaren form a part of a ring-depression. The bedrock map of the Kopparberg County shows – somewhat displaced to the north – a circle of the same size. In the list of rocks this rock is named granite-syenite. This sounds like the crossbreeding of hors and zebra in zoology. In fact in the eastern part of the circular area there is a typical rapakivi-granite, which weathers and crumbles very easily. It consists of several cm-wide potash feldspar crystals, mantled by plagioclase and plenty of hornblende. In the north-western part the rock consists of red-brown microcline of up to 5 cm size and large quantities of light green epidote, only. Some samples are completely free from visible quartz, others contain an insignificant concentration.

At (Pos. Ak) there are large-scale shatter cones to be seen in the boulders on the beach together with dark red pseudotachylites. Such large potash feldspar crystals have been recognized at other sites of supposed astroblemes, might have been developed out of the shattered rock during the time the bedrock still was partly melt due to the chock. Due to the combination of shatter cones and pseudotachylites this site is worth of further investigation.

At (Pos. Bi), about 100 m north of the forest road beginning at (Pos. Bj), there is a block of Ordovician calcite, weighing about 50 kg. It has no detectable layering, consist of a sintered mixture of calcite- and quartz powder. To survive under geological times it must have been covered by other debris, originating from the fall of the meteorite. Since the border of the Siljan-meteorite is not very far away, it could originate there from or belong to the supposed Ljugaren-meteorite. See Fig. 27a and Fig. 27b.

Fig. 27a: Reconstructed calcite from north side of Lake Ljugaren

Fig. 27b: Reconstructed calcite (Rear side of sample Fig. 27a)

At the same location there are several boulders, consisting of the brown-red microcline and epidote, only. The epidote is light green in colour and must have been a melt/liquid, since it penetrated the mesh of loose feldspat crystals as a vein. Note that the microcline is definitely darker than normal in granite or pegmatite. The veins contain fragments of the feldspar and of other epidote-minerals like orthite. See Fig. 27c.

Fig. 27c: Syenite (microcline and epidot, only), formed from calcite powder and rapakivi granite

The genesis of this feldspar-epidote rock (about 50% of each) we might imagine as follows: Directly after the impact of the meteorite the bedrock got melt or partly melt. This condition lasted for very long times, years or thousands of years, depending on the size of the melt body. During this long time quartz left the system by aid of supercritical water to cooler regions (this is seen in the nearby Siljan astrobleme). The feldspar crystals grew in size by 'cannibalism'. The residual debris of the previous granite, together with debris from the Ordovician limestone, was attacked by the water-vapour present. Calcite, water and calcite-feldspar reacted to zoisite according to

$$CaCO_3 + 3(CaAl_2Si_2O_8) + H_2O \leftrightarrow 2(Ca_2Al_3Si_3O_{12}(OH)) + CO_2$$

This zoisite (or epidote) reacted with little water present to an eutectic melt or - with much water present - to a liquid, saturated with zoisite. Both filled the empty space between the mesh of potash-feldspar crystals.

This combination – dark microcline and light-green epidote - is seen in several other of the described supposed astroblemes.

Along the forest road from (Pos. Bj) to the stop for (Pos. Bi), on the west side of this road, there are several bolders, affected by the impact. One of these consists mainly of (previously) pulverised and now sintered calcite, see Fig. 27d.

Fig. 27d: Sample of reconstructed Ordovician calcite

7.9 THE SUPPOSED LAKE BALUNGEN-ASTROBLEME

Despite its evident ring shape, consisting of several lakes, up to date only one single find has been made which relates to a supposed astrobleme, viz. a piece of a soevite at (Pos. Al), unfortunately in an esker; this means, that the sample could emanate from anywhere. More research is necessary. The site has been visited only once up to date.

7.10 THE LAKE HUMMELN-ASTROBLEME

Due to very rich finds in the field the prefix ‘supposed’ has been avoided here. There is no doubt, that this astrobleme is a real one. This supports the assumption that several or all of the other astroblemes are real, too.

In Sweden large lakes have only one name, i.e. not the prefix ‘lake’. Examples are Vänern, Vättern, Siljan, Dellen, Mien and Hummeln. The last four names are well known astroblemes. Hummeln is a lake 15 km NW of Oscarshamn. Our Lake Hummeln (Hummelsjö) is a small lake 8 km SW of the town of Vansbro in Central Sweden and 75 km SW of the centre of the Lake Siljan-astrobleme. The similarity of the name and the fact that this lake with a round form lies straight on the line of impact of all the other here described supposed astroblemes made this author interested. The lake is semicircular, with the round shore to the north. The diameter of the astrobleme appears to be about 1,3 km. It is reached from state-road 71, turning on a forest road, which starts 100 m west of a railway viaduct, before the village Rågsveden. The forest road heads to the east. After about 5 km at (Pos. Ap) one is in the middle of a large deforested area at the highest point of the road. There from the whole field of prospecting can be overlooked. East of that point is an area that has been cleared by fire from shrub and vegetation on ground. There all boulders are clean from lichen and mosses. There almost all boulders have a reddish-brown appearance and most of them are affected by the astrobleme. The unaffected granite there has a grain size of about 5 mm with pale-orange potash feldspar, white albite and clear quartz in same proportions. The affected stone shows pseudotachylites, which often consist of three layers: The middle layer consists of the brown melt, boarded by later layers of quartz. This damage is quite easily found.

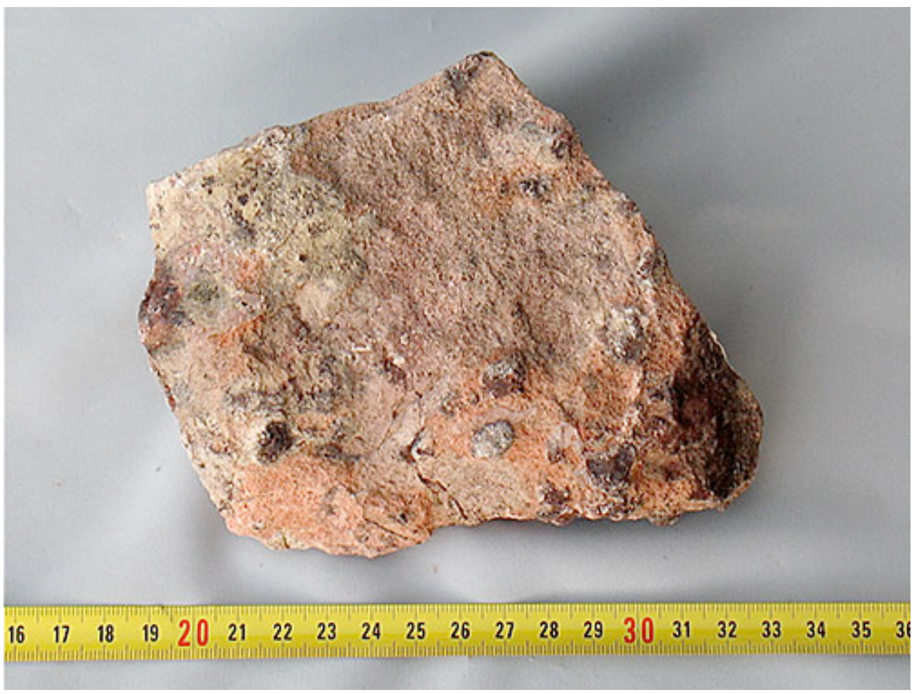

Fig. 28: Orange "volcanic" ash

Another type of damage is a rock looking like an orange volcanic ash, Fig. 28. Its constituents are mainly quartz grains of < 0.5 mm and some much larger rounded quartz grains. The rock is similar to that from the Lake Stora Flaten-astrobleme, there Fig. 7.

Another type of rock consists of potash feldspar and quartz. The feldspar is deep orange, does not show cleavage, it looks like relatively fast-reconstructed granite.

A further type of rock exist here, but is not very common here. The same type has been found in the Lake Flosjö-astrobleme and is shown there in Fig. 13. On the first sight it looks like red porphyry, but it is not a porphyry, because completely free from free quartz and therefore a syenite. Its texture looks by free eye as a melt; at 10 times magnification one sees that the matrix consist of inter-grown feldspar crystals with local cleavage. The colour is deep red-brown, like microcline from mylonite. A tentative explanation of this rock is the following: The impact of the falling meteorite has pulverised the bedrock and created high local temperatures. Steam leached this slurry, removed quartz (therefore so much quartz annealing at other sites) and left the pure feldspar slurry to recrystalize. This red-brown rock is found at sites of astroblemes, only. The hypothesis explains, too, the heavy occurrence of free quartz at (Pos. Aq) in the Siljan-astrobleme, where blocks of several hundreds of kilograms of pure milky quartz can be seen.

Fig. 29: Pink grey parts: Melt; light parts: Damaged original granite (Pos. Ap).

Fig. 30: Red-brown melt and reconstructed granite (Pos. Ap).

The most convincing evidence for an astrobleme are blocks rich in melt (see Fig. 30 and Fig. 31). They occur scanty, but can be found. Those, this author has found, contained very much melt, which is completely different from that at other sites. Due to a rich content of tiny black particles the melt is gray. The particles – size some tenths of a millimetre – look like hematite, but are magnetic (= maghemite). Some parts of the quartz layers are dyed pink like by erythrine. Diffraction analyses, made by Riksmuseet (Doc. Skogby) showed, that the pink layers consist of the mineral piedmontite. Black dikes appear, too.

Having compared the melt from Lake Siljan och that from Lake Hummeln nobody can claim, that they are identical. Therefore the latter must be genuine and autochtonous, which proves, that Lake Hummeln is an astrobleme of its own. Possibly – due to its small size – the falling body did not evaporate completely and therefore the chemistry of the impact process is another here; we see here remains of the falling meteorite.

Fig. 31: Left part: Cracks in the solid roof, filled with melt. Right part: Dots of residual eutectic melt.

There is a further peculiarity, to be mentioned: Most of the granite there must have been partly melt right through, having the appearance like pea-soup. The peas were the grains of quartz and feldspar (microcline and albite) and the soup was the liquid phase. During cooling part of the liquid phase crystallized upon pre-existing crystals, until the eutectic composition has been reached and the remainder of the melt solidified instantaneously. Patches of 5 to 10 mm of the brown eutectic melt are seen everywhere, see Fig. 30 and Fig. 31 (right part of figure). This liquid was at the bottom of the crater; its surface finally solidified, like the surface of a magma lake in a volcanic crater. Slides or other tectonic movement has cracked the solid surface, the underlying (near eutectic) melt poured up and filled the cracks, see left part of Fig. 31, but also Fig. 29. Between the instant of meteorite fall and filling cracks in the solidified surface there can be many years. Due to fast cooling this second melt is very fine-grained and does not contain fragments of the side-rock, like in the samples from the Lake Siljan astrobleme.

Fig. 32: Even blocks of dolerite, which happened to be at the site of impact, have been remelted and form a sharp zigzag border with the partly melted granite.

Fig. 33 from the Hummelsjö-astrobleme shows a large piece of granite, containing fragments of pieces of flint-like rock. The flint has been broken into fragments by an instantaneous melt, that has enclosed the flint. There is no sign of melting or digestion of the flint, like it is seen in other sites, where a granite magma advances and gradually digests the country-rock. Compare this figure with Fig. 8a from capture 7.2. In the Hummelsjö-sample the granite was not completely melt, but consisted of crystals, floating in a partial melt. In the former Lake Stora Flaten-sample Fig. 8a the melt was hotter and formed a single phase liquid.

One kilometre south of the astrobleme site there is a hydropower-station in the river Västerdalälven. Here - downstream the dam - large areas of the bedrock are exposed. No trace of impact-affected rock is seen. Therefore the Hummelsjö-astrobleme has to be a small one or lying mainly to the north of the power station and has nothing to do with the recently discovered Rågsveden-astrobleme, which is at about 7 km to the west.


Fig. 33: Partly melted and afterwards recrystallized granite containing pieces of flintlike rock.

A recent find – see Fig. 33a – shows the in time different processes in this astrobleme. The brown melt right in the picture, which solidified first, was intruded by a thin (in the picture horizontal) quatz-vein. Next a semifluid 'paste' engulfed the brown piece, solidified finally. Last a quartz-vein of different color broke through the now solid 'paste'. Probably in time different pulses of quartz-solution used the same fissure and deposited their color. Between two of these a lens-like residue from the 'paste' is seen.
This shows that – hidden by a cover - there existed different melts long after the impact. Compare this with Fig. 33.


Fig. 33a: Melts of different melting point within the same sample. Coin 25 mm diameter.

7.11 THE SUPPOSED LAKE ORE-ASTROBEME

SE of the village Furudal (Pos. Ay) there are two interconnected lakes with name Oresjön and Södersjön. Both are rather circular and therefore object of our interest. The centre of Oresjön is at (Pos. Az) and that of Södersjön at (Pos. Ba). The radius of the former is 1,3 km, that of the latter 0,7 km. They are situated within the ring dike of the Lake Siljan-astrobleme.
After retreat of the last ice-cover the river Oreälv had its pass right through the lakes to the south, reached finally Lake Siljan at a place, where later the town of Rättvik has been founded. Enormous glacifluvial deposits fill the former stream valley; the depth of these deposits is at least 20 meter. This is seen in holes of up to 100 m crest-diameter, formerly filled by icebergs. Maybe by uplift of the land or by damming of the former flow at Furudal the river Oreälven took a new pass to the west and now is discharging its water into Lake Orsa.

The above two round structures are too large to be floating icebergs. Running water would have cut them to stripes, like seen in the valley west of Gärdsjö. Therefore they could be small astroblemes, simultaneous falls with the large Siljan impact. In that case during ice ages the craters have been filled with ice. Running water on top of that ice cannot deepen it more than to the local erosion base. Afterward, certainly the ice gradually melted away and has left two deep pits. We do not know the depth of the lakes: A sounding and construction of a bottom profile (best to the solid rock) would be valuable for resolution of the question. Deep holes would indicate astroblemes.

The bedrock of the whole area nearby consists of a light gray to white fine-grained sandstone from the Silurian, called Orsasandstone. There the stone is very uniform in colour and texture.

From the (Pos. Bb) starts a hardly visible carriageway heading east, enclosed by walls of amelioration stones, picked by farmers from the ground. There in the beginning are several blocks of the local sandstone, which actually are breccias, containing fragments of different red dyed sandstones, see Fig. 34; the left sample is the shattered sandstone, the right sample the unaffected sandstone from nearby. There is no doubt, that these fragments of a catastrophic event have been compacted to a new rock. Only an impact can do this. Now the question is: Which impact - The Lake Siljan astrobleme or the supposed small astroblemes in Lake Ore?

However, there can be another explanation: In the sandstone quarry at Kallmora in the northern part of the Siljan ringdike there exist similar sandstones with inclusions of dried clay, evidently transported there by wind. In Chapter 8. this question will be discussed more in detail under the heading 'An attempt to understand the origin of the Orsa-sandstone'.

Fig. 34: Right part: Undamaged Silurian sandstone from nearby. Left part: Same sandstone after catastrophic event.

There is one interesting observation more. At (Pos. Bc), in the middle of local sandstone, there is a ridge of granite, about 200 meter long and 15 meter high, heading 12°E. Since it is parallel to the local perimeter of the supposed astrobleme Södersjön, it could be a spall from that and not from the Lake Siljan astrobleme; the heading of this 'spall' is at 90° to the perimeter of the Lake Siljan astrobleme.

The above findings indicate, that the two small lakes very well could be astroblemes, too.

7.12 THE SUPPOSED RÅGSVEDEN-ASTROBLEME

During summer 2010 a further site of a supposed astrobleme has been recognized south of the village Rågsveden. Nothing in the topography of the landscape tells of an impact there, but instead finds of impact-affected samples in the local moraine. This site is in line with the other sites of astroblemes, i.e. in the left end of the stray-ellipse. The samples found are a bolder of breccia, welded together by a brown melt, boulders penetrated by a quartz-rich melt and boulders evidently containing residues of a slate, together with granite fragments. As known, the series of Ordovician rocks contained a layer of shale, too, the s.c. Tretaspis-shale. Positions to localize the finds are:

- (Pos. Be): Start at that point on an about 1 km long forest road, heading south. Along this road (in the sand of the ditches) finds can be made.
- (Pos. Bf): Crossroad there. Take the road to the south. After
- 1 km new road to west. After 200 m
- (Pos. Bg): Cut through a sand ridge; here the slate-containing samples easily are found.
- About 1,5 km to the South at (Pos. Bh) no trace of impact damage is to be seen. Evidently the supposed Rågsveden-astrobleme is very local one.

Note that in the environments there are very large (size of a small home) local boulders. This has been observed at several other astroblemes: Evidently the bedrock has been shattered by the impact; later on it cured, but broke up at old cracks again during glaciation.

Both at the Hummelsjö-astrobleme and at the Rågsveden-astrobleme, too, samples showing a quartz-rich greenish melt can be found. Evidently this is a melt formed from little water and plenty of different rock minerals at some time after the impact. With other words: It is not a late hydro-thermal impregnation of the bedrock with water-transported quartz!

7.13 THE SUPPOSED KVIEN-ASTROBLEME

The former natural lake Kvien is now dammed and used as a water reservoir for a hydropower station on its southern end. The distance of the power station to the nearest town Malung is 30 km and the distance to the centre of the Siljan astrobleme 95 km. The lake Kvien is narrow and 15 km long, has by no means the appearance of an astrobleme. The heights difference between the lake level and the exit level in the power station is about 20 meter. The coordinates (Pos. Bk) of the northern dam are: 138940E/679435N.

The dam is built from locally blasted rock; we do not know, if there is a particular quarry for this rock or if material from the blasting of the tube has been used in the dam. Probably the latter is the case. The power station is fully automatic, there is nobody there to be interrogated. The core of the dam certainly consist of clay and gravel from some nearby gravel-pit. This core is not visible, is completely covered by the blasted stone.
Already several years ago this author has reacted on the strange type of visible stone. Now, in connection with the discovery of a series of supposed astroblemes on a line from SW to NE he returned to Kvien, since this site lies more or less on that line.

Two types of stones prevail:
-The first is a heavily sheared stone with gliding planes (here brown tachylites), with gliding planes at a distance of some few millimetres. The gliding lengths cannot be determined, can be centimetres. The basic material is rich in quartz. Fig. 3 from the Siljan-astrobleme shows this type of gliding. Fig. 35 from Kvien is the equivalent of Fig. 3.
-The second type is a brown stone, containing substantial quantities of a melt phase on both sides of an intruding quartz vein. This is seen in Fig. 36. Figures 37 and 38 are the opposite sides of the same sample. Also here by visual inspection melt material is seen. This type of material is not as common as the tachylites.

Fig. 35: Sheared stone sample with tachylites from Lake Kvien

Fig. 36: Melt (pseudotachylite) from Lake Kvien

Fig. 37: Melt from Lake Kvien

Fig. 38: Rear side of sample Fig.37

It is known that previously there has been a pressing of more westerly rock massives with a force vector pointing easterly. This effect is seen in the sandstones (quartzite) near Malung. These are bent or raised up to vertical position, but not sheared. This effect could explain the tachylites, but not the massive melts in the second type of material. Therefore the question of the origin of these peculiar rocks is unresolved.
About 0,5 km from the dam there starts quite different rocks, a granite with very large brown red microcline crystals. Due to the load of the Holocene ice-sheet this granite has been cracked in very large blocks, the largest of these measuring about 20x10x8 meters.

Without knowing, wherefrom the massif melts originate and finding other types of samples too, it is very questionable to suppose an astrobleme to be the source of the found samples.

8. AN ATTEMPT TO UNDERSTAND THE ORIGIN OF THE ORSA-SANDSTONE

The preset study has let to a spin-off, viz. to the understanding of the origin of the Orsa sandstone. Since this sandstone is completely free from fossils, it could not up to date be placed in time scale; however, it is allocated to the Silurian. According to studies by professor Thorslund there is a substantial gap in time between the highest known sedimentary horizon and the Orsa sandstone. In fact, the Orsa sandstone belongs to the Lower Devon and has been formed by the Siljan impact 377 million years ago.

Let us investigate the facts:
-The Orsa sandstone is free of fossils
-The purest samples consist of white quartz grains and a varying content of calcite (right part of Fig. 34). Other samples, particularly those from the quarry at Kallmora, are dyed red-brown of different shades. Even rose samples, dyed by pulverized microcline occur; see Fig. 39. Further there occur samples, rich in fragments of dried clay; these fragments have no order in-between, see Fig. 40. There exists a mix of died and white sandstone, too, see Fig. 41. Evidently volumes of heavily dyed loose sand got in contact with another volume of white sand.

Fig. 39: Orsa sandstone from Kalmora. Upper part: Undyed white sandstone. Middle part: Sandstone dyed by pulverised microcline

Fig. 40: Orsa sandstone from Kallmora. Light brown background: Mixture of the dying agent and white qurtz. Dark brown spots: Residues of the clay formed in depressions before the avalache, that mixed the unconsolidated airborne sediments

Fig. 41: Orsa sandstone from Kallmora. Three grades of brown sandstone, in contact with white massive white sandstone

The geological regional map /13/ around the astrobleme shows a ring dike of Ordovician and Silurian sediment, that have been preserved in the dike formed by the impact, described by Melosh /11/ as a ‘peak ring crater’ in his

Fig.8.14 (b). The whole ring consists of three part-rings: The innermost consists of Ordovician calcite, the middle one of the Orsa sandstone (treated her) and the outermost of Ordovician calcite again.
Further away from the impact no Orsa sandstone does exist. In the inner carbonate ring the originally horizontal calcite sheets are raised to a steep angle; in the outer ring they are slightly tilted, only. There seems to be a trench between these two carbonate rings, filled-up with the sand, later forming the sandstone. This trench can be seen going around the centre of the astrobleme all the way round.

Some important finds are the key to understanding the formation of the Orsa sandstone: At the beach of Lake Siljan, below the cementary of Rättvik, there are several boulders of calcite and of a mix of calcite and Orsa sandstone. This site can be reached at low-water in Siljan, only. These boulders are not original, layered and fossiloferous Ordovician calcite, but reconstructed calcite, formed from - during the impact - pulverised calcite. This secondary calcite contains different amounts of small quartz grains, as shown in Fig. 4b.
By the same token there exists a reconstructed sandstone, formed from
A) previous sand layers (sediments between Ordovicium and Lower Devon) or from
B) the shattered granite in the center of the impact.

From Fig. 1 it is evident, that also the granite in the basement below the cover of later sediments has been affected very much. In the centre the sediments and the granite have been evaporated, crushed to powder and blown up into the atmosphere, together with droplets of melt. Hours later this atmospheric load started to fall out, larger particles first, the smallest last; carbonate particles below quartz-particles. This process may have taken weeks and month.
It is known from/13/, that below the Orsa sandstone there is a conglomerate layer. In our explanation then followed quartz fragments and finally what was left of the droplets of melt, now of course in solid form. The landscape probably looked like snow in the Alps, the upper surface of the ‘snow’ somewhat dirty. The dirt reacted with rainwater and has been transformed into a red-brown clay, which collected in depressions and dried up there.

At that instant the new sediment had no firmness at all, avalanches started easily like snow in the Alps. These avalanches mixed the originally white sand sediment with flakes of the dried clay in a chaotic manner. Also slightly consolidated volumes were mixed up, giving a primordial stone, where reconstructed calcite is mixed up with reconstructed sandstone. Such samples have been found at Rättvik on the beach, look like intercalated hands, where fingers of the one hand are intercalated with fingers of the other hand, see Fig. 42 and 43 (IMG_2016 and 2018).

These figures show the front side and the rear side of the same sample. Note, how distinct reconstructed calcite is separated from the sandstone.

Fig. 42: Pieces of reconstructed brown Orsa sandstone and reconstructed grey limestone. The whole material has been pulverised during the impact. Fresh broken surface of same sample as in Fig. 43.

Fig. 43: Same sample as in fig. 42, but surface exposed to erosion. Pieces of reconstructed limestone separated from reconstructed Orsa sandstone

This is the final proof that reconstructed calcite and Orsa sandstone are contemporaneous and formed by the impact of the Siljan meteorite.

The clay particles may contain residues from the meteorite, t.ex. iridium or some other unusual element. The Chicxulub meteorite has been detected by clay-samples from Italy and Denmark, too.

Dyed samples of the Orsa sandstone may show bleaching dot, up to a centimetre wide. The reducing agent is of course carbon in some form. The carbon may very well be of terrestric origin; however, it could also be of meteoric origin, from a CI-chondrite. Therefore even the centre of the bleaching dots should be examined for unusual elements.

9. DISCUSSION

About 377 million years ago a large meteorite hit the central part of the present County Dalecarlia in Sweden. To day we know the size of the crater (figures like 52, 65 and 75 km diameter of the outer rim of the crater have been mentioned); however, we do neither know the kinetic energy, nor the mass, the composition (density), the diameter or the speed at touch-down. Estimates of these data in literature are pure guesses.
Certainly its mass, diameter and speed must have been substantial; such meteorites get instantly heated by their compression and evaporate completely. Therefore we never will be able to disclose the nature of that meteorite.
Stony meteorites consist of cosmic debris, of minor particles bound together to a body by mass forces only, not by chemical forces like in a solid body. Therefore such meteorites have the tendency to crack into smaller pieces during passage through the Earth' atmosphere. As an example the very young Chiemsee-fall (Bayern, south Germany) can be mentioned. It is so new, that originally the minor craters, that had been observed here and there, have been interpreted as lost bombs after bombarding of Munich during the Second World War.

Lake Siljan

Field evidence points towards that the fall of the Siljan meteorite was not an isolated event, but consisted of a shower of simultaneous meteorites, fragments of the original meteorite. Such showers lie always along a line, like in the Chiemsee-fall. To day we can study the - by weathering grossly modified - remnants of a meteorite fall; we call the damage astrobleme.
This author has during many years studied the Siljan astrobleme and thus attained a solid knowledge of the rocks formed instantly by a fall and those

formed later in the debris due to the residual heat, lasting hundreds of years (depending on the size of the impact).
New rocks are formed in the seconds of the impact, during the following years, when the unstable crater rim slides down into a water-filled ring-dike and even later in the melt or semi-melt, covered by debris in central parts of the impact.
As a physicist this author also knows a lot on the mechanism of the impact – the first seconds after touch-down – which is useful to understand the formation of the different rocks at different instants and sites.

Other astroblemes

With the experience from the Siljan astrobleme he started to study a peculiar site north of the town of Dala-Järna, where several oblique lakes formed a system of an interrupted ring dike. Soon the same or similar rock samples have been discovered, which indicated, that this ring could be an astrobleme, too. In this report he has given the coordinate of all sites, thus everybody can convince himself of their existence. The rocks are there! Somebody may propose, that they have come there from the Siljan impact by other geological processes like having been thrown there or transporter there by Quaternary ice transport. This point will be discussed later in this chapter.
With this experience it was easier to discover other sites, like the Dala-Floda astrobleme, that belonging to Långsjön and that SW of Vansbro near Hummelsjön. This latter is the one, which is richest in finds: Practically every bolder there is affected by that impact.
All the finds lie along a line from SW to NE between the village of Rågsveden in the SW and the Lake Balungen in NE.

Size of the area of astroblemes

At most sites the bedrock is covered by till from the latest glaciation; practically all samples have been found in the till. Even there it is difficult to find something, because – due to the high humidity - all boulders here are covered with moss or lichen. Only there where a forest fire cleaned the stones or where forest-ploughing has unearthed 'clean' stones, which can be inspected.
Therefore even within the Siljan astrobleme it is difficult to find signs of the impact: One has to look for areas of forest fires, forest ploughing, beaches, amelioration piles, river beds, gravel pits and road sides, where blasting has taken place. The same is of course true for all other sites.
Therefore a site can be much larger, than we can see it: The peripheral parts disappear below moss and lichen.

Sediment burden at the instant of impact

At the instant of impact 377 million years ago the bedrock was covered with sediments from the Ordovician, the Silurian and the Lower Devonian. Thorslund /5/ estimated the thickness of the Ordovician in Dalecarlia to 130 m. Petalas /6/ has studied the sedimentary petrology of the Orsa sandstone. Randot /7/ estimates the thickness of the whole burden up to the impact to 500 m. Grieve /8/ up to 1000 m, Collini /9/ and Lindström /10/ up to 2000 m. Therefore much of the impact energy has been lost in these sediments. During the past 377 millions of years these have been eroded by weathering. To day we are looking on a bedrock surface, which is even lower than that surface at the instant of impact.
With other words: We are looking on a deep level of the astrobleme! Still there is very much to see, e.g. previously melt rock!

Effect of long-time heating to high temperatures of deep volumes

As mentioned earlier, heat is not only generated by the reversible adiabatic compression of the rock during the seconds of the impact, but also due to the irreversible friction between fragments of the rock. Since shattered granite is a poor conductor of heat this heat stays for very long time. E.g. in combination with supercritical steam, quartz is dissolved and transported to cooler regions; therefore are the samples from around Trollberget in the Siljan astrobleme, containing thick 'schlieren' of melt, free of visible quartz. It is this quartz that on a higher level glued together the shattered fragments to a solid rock, free from cavities to host abiogenic gas.
Samples from the Lake Hummeln astrobleme show, that the previous melt must have had the structure of a pea-soup: Still solid crystals of microcline and some quartz are seen to be floating in a liquid phase (the eutectic water-quartz-microcline-muscovite).

PDF as a means for safe detection of an impact

PDF = Planar Deformation Features are deformations in feldspar or quartz, generated by a passing wave of very high pressure. Microscopic parts of the quartz crystal are displaced from their normal position in the lattice. This defect can be seen on 30 micrometer thin samples, inspected by the mineralogic microscope with parallel or antiparallel polarizers. If present, they are a very clear sign for very high pressures, attained in impacts, only. The PDF's cannot be seen in advance by eye or with a magnifier. This makes the selection of samples for preparation for the expensive micromounts a hazard. Further, there is the risk, that the above-mentioned long-time heating of the rock has annealed a sample, which originally had PDF's. Therefore: Existing PDF's are a reliable proof for the sample to originate from an astrobleme. Missing PDF's do not tell anything: The sample has nothing to do with an astrobleme or it originates from one, but for the above reasons is free from PDF's.

Iridium in samples

Iridium on Earth is a very rare element, but is more frequent in space. Therefore prove high concentrations of iridium in suspected samples, that these originate from an astrobleme. Again, missing iridium does not tell anything: Either the suspected sample does not belong to an astrobleme, or it does, but the meteorite did not contain iridium.

This author has no access to micromounts, a microscope for photography or to iridium-analyses. Therefore the above proofs could not been done. However, he has carefully compared astrobleme-samples from the Siljan with those from the other supposed astroblemes and accepted the verdict 'astrobleme' at complete coincidence of the samples, only.
At some of the supposed astroblemes the quantity and quality of the samples is not sufficient, at others it is very good.
For example: To my opinion the supposed astroblemes Dala-Floda, Dala-Järna and Hummelsjön are real astroblemes. This makes several of the others very probable.

Reconstructed rock

During the instant of impact the basement rock is shattered and partly pulverised. Later on (during years to thousands of years) this debris forms new rock. This is the meaning of the term 'reconstructed rock'. There are two types of reconstructed rock: One is formed at or near the surface, the other at depth.
Formed at the surface: The impact pulverises previous rocks near the surface; in our case this will be the sediment above the basement rock and some granite. All previous textures like fossils or Ordovician discontinuity surfaces have been erased. Due to friction in the dust cloud grains of quartz can assume the shape of lenses. After settlement the mixture of quartz (from Silurian and/or from the granite basement) and calcite (from Ordovician) forms a new rock, free of all previous texture. Blocks of this type of rock are found in spring (low water level in the lake) at the shore of Lake Siljan, below the graveyard at Rättviks church, see Fig. 4b or Fig. 27a or Fig. 27b. In front of library at Rättvik there is a large calcite boulder of that reconstructed type exposed, too.

Formed at depth: At depth the previous rock (here mainly granite) is shattered to fragments. Since this region is very hot for very long time, microcline crystals grow in size by consuming smaller ones. A size of 5 cm is not uncommon. Between the grains of the shattered rock there is an eutectic melt, that finally solidifies, see Fig. 14 and Fig. 16a. Quartz is destilled off.

Inclusions of calcite

In the Lake Stora Flaten- and in the Lake Flosjön-astrobleme at several locations pieces of reconstructed rock (granite) have been found that contain some cm^3 large fragments of the Ordovician calcite. Note: These are isolated fragments, not later impregnations with dissolved calcite. See Fig. 8a and Fig. 16b.
This should be a far better proof of an astrobleme origin of these samples than PDF, because PDF can anneal and disappear, but calcite inclusions not.

Large boulders in the moraine

As previously mentioned, locally in depressions there are accumulations of local boulders with sharp edges (hardly any transport distance). These seem to be more frequent here than in terrain, not hit by a meteorite. However, this is not a very strong evidence for an astrobleme, but has to be noted. The area one to two kilometres south of (Pos. Bm) is just such a site.

During times of glaciation (a larger number of glaciations have taken place) an ice sheet of one or two kilometres of thickness slowly moves over the bedrock, transporting away any rock broken off the bedrock. The latter is most ground at elevated positions, creating polished, smooth hillocks. This is the standard situation: Moraine in depressions and polished tops of hills. Therefore it is astonishing to see hills at sites of astroblemes, on their top covered by large, sharp fragments of the underlying rock. The following positions are just an example: Pos. K, Pos. Bl, and Pos. Bm. A plausible explanation for this fact might be: At these sites the original bedrock has been deeply shattered by the impact of a meteorite. During geological times between 377 million years ago and to day first the sedimentary overburden has been removed by weathering and recently several tenths of meters by repeated glaciations. Towards the end of the last glaciation – during retreat of the ice sheet – the ice-tongue lost contact with the remaining ice sheet to the north, had changed to a 'dead ice'; this no longer moves. However, the temperature is still around zero Centigrade. Melt water penetrated and filled the old cracks; freezing during night bent loose the blocks, which remained resting at that site.

Similarity between samples from different sites

Lake Siljan: Concerning samples of pure melt these have been up to date found in the till, only, not in outcrops. Such outcrops probably exist, the fragile material has been broken off during the latest ice-age. In these samples the melt phase consist of a fine-grained matrix, greyish or brown in colour, with included pieces of burned granite. No free quarts is to be seen in either the melt nor the enclosing burned granite. This quarts has later (years

and thousands of years later) been distilled upwards and filled all fissures in the shattered overburden, now exposed.
Inclusions of calcite have not been found in Siljan.
Reconstructed rocks, consisting of calcite powder (from Ordovicium) and quarts sand (from Silurian) are found at Rättvik. These samples are completely free from fossils. One large sample is shown outside the City Library.
Lake Flosjö: Near and on top of Bodberget (Pos. N) plenty of minor and larger boulders can be found, which consist of shattered granite, percolated by a dark melt, to day consisting of chlorite. This type of melt has not been seen in the Siljan-astrobleme.
At the centre of this astrobleme at (Pos. Q) boulders may be found, containing a dark brown melt, but in other samples also containing a black glassy melt. These dark melts do not occur in Siljan.
Several inclusions of calcite nodules in the shattered 'granite' have been found.
Lake Snesen-Storflaten: Plenty of brown, homogeneous melt found, enclosing crushed pieces of the bedrock. Evidently this melt has been pressed from a distant point into a heap of crushed stone.
Inclusions of calcite are found, too. These are seen inside recently broken samples, only. Other samples show on their surfaces cavities, which once had been filled by calcite, which now has gone. These calcite nodules are not late dikes, but are splinters of Ordovician limestone, created during the seconds of the impact.
SW of Vansbro: This site is very rich in all sort of material: Melts, reconstructed 'granite', sintered ashes, two generations of melts in contact with one another. This observation has been explained previously in this paper. We have not seen it in the other sites.

In none of the astroblemes mentioned here outcrops of melt have been found. The only suspect place for this is the top of the hill Bodberget: There the bedrock consists of a 'granite', consisting of about 50% albite and some quarts and of 50% dark minerals like biotite and hornblende. Such a high content of dark minerals is not known from normal granite. Could this granite be a 'reconstructed rock', having received material from the vaporizing meteorite? If the falling meteorite had been a so-called CI-chondrite, this would support the hypothesis. These CI-chondrites contain large amounts of water, organic compounds and of hydrous phyllosilicates.

One feature, common to most of the sites from Lake Kvien in SW to Lake Ljugaren in NE should be mentioned: The existence of very large orthoclase crystals in granite. These may be 50 times larger in volume than the average orthoclase crystals nearby! A tentative explanation is the following: Due to the residual heat after the impact the granite in question has been heated for tens and hundreds of years. Even without partial melting the mobility of the ions is orders of magnitude higher than at room temperature, smaller crystals are ‘eaten up’ by larger ones. If partial melting has occurred, the ion-transport is still faster. Crystals of up to 5 cm length have been seen. The southern side of Lake Ljugaren consists of such granite.

How could astrobleme samples, originating from the Siljan astrobleme, reach the positions of the supposed astroblemes?

Since several scientists of the Swedish geological community evidently believe this, I have the task to test these possibilities. In principle there exist two ways, only, to move samples from the Siljan astrobleme to other sites in Dalecarlia:

A) The samples have been thrown there and to all other locations around the Siljan astrobleme during the seconds of the impact
B) The samples have been transported from their original sites according to A) to the present downstream locations during the latest glaciation

Let us test the feasibility of these two modes:

Mode A). For nearby locations this mode could be possible. However, these projectiles do not have cosmic speed, but more terrestric speed and will not penetrate the thick cover of young sediments to any depth. Since we during the following 377 millions of years have lost between 1 to 2 km of sediments by erosion, it is completely impossible, that inherently weak casts – located within these sediments – should have survived a series of may-be ten glaciations.

Mode B). The glacial ice in Dalecarlia was flowing from NNW to SSE. Taking the richest and most distant location – the astrobleme at Vansbro, south of Hummelsjön, as an example - we cannot imagine, how the ice flow should change its direction by 90˚, deposit a lot of stones from Siljan within a very limited location and then turn back again into the normal ice-flow direction. Rather it is so, that the bedrock at that site contains the roots of a local astrobleme and the ice-flow has broken free the boulders, we see today.

There is one more important argument for the supposed local origin of the collected samples far away of Lake Siljan: Samples – thrown there by the impact – behave like stone in a quarry during blasting: There is no time to change in chemistry or composition! These ejecta may be crushed, but are never sealed by quarts or melt. Sealing is a much later process in the history of an astrobleme.

By these arguments I believe to have demonstrated, that the supposed astroblemes outside Siljan have to be real ones.

ABOUT THE AUTHOR

The author is PhD in physics from the Technical University of Stuttgart and BS in geology from the University of Uppsala. Today he is retired. During his active time he has worked at ABB in Ludvika with research on the physics of material for transformers. As geologist he has worked for LKAB Prospekterings AB and teaches Geosciences for local laymen.

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COORDINATES OF SITES

(The Swedish National Grid RT90 is used here)

Pos. A	:		
Pos. B	:	144640E/675580N	Garsås, gravel pit at railway
Pos. C	:	144620E/675470N	Garsås, beach
Pos. D	:	145425E/675125N	Stumsnäs, pier
Pos. F	:	143210E/672525N	Turn-off from public road to Långtjärn
Pos. G	:	143164E/672880N	Långtjärn, at the dead birch
Pos. H	:	143175E/672980N	Small gravel pit 1km N Långtjärn
Pos. I	:	143210E/672540N	Turning towards end of road
Pos. J	:	143128E/672652N	End of road
Pos. K	:	142825E/672280N	Giant boulders at Lake St.Snesen Pos. L
Pos. L	:	143110E/672225N	Gravel pit at Lake St. Baggbod-Örad
Pos. M	:	144250E/671520N	Centre of Lake Flosjö-astrobleme
Pos. N	:	144945E/671630N	Saddle between Bodberg and Forsbodarna
Pos. O	:	144930E/671750N	Recently build forest road
Pos. P	:	144935E/671775N	Ploughed area of deforestation
Pos. Q	:	144315E/671440N	Old gravel pit at Trolldalarna
Pos. R	:	144750E/673425N	Hill Tutberget on Harpick-island
Pos. S	:	143540E/673850N	Centre of Lake Vådsjö-astrobleme
Pos. T	:	143649E/673780N	Gravel pit inside Vådsjö-astrobleme
Pos. U	:	143580E/673425N	Gravel pit at north end of Lake Långsjön
Pos. V	:	143750E/671905N	Slope on west side of Flosjö-astrobleme
Pos. W	:	143630E/671725N	Protected area W of Flosjö-astrobleme
Pos. X	:	143970E/673230N	Centre of Lake Långsjö-astrobleme
Pos. Y	:	143535E/674060N	Turning of road in Lake Vådsjö-astrobleme
Pos. Z	:	143437E/674099N	Gravel pit in Lake Vådsjö-astrobleme
Pos. Aa	:	144234E/673060N	Quarry in Lake Långsjö-astrobleme
Pos. Ab	:	144960E/673790N	Cairn on Storön in Siljansnäs-astrobleme
Pos. Ac	:	144789E/674043N	Amelioration cairn in Siljansnäs
Pos. Ad	:	146300E/673950N	Centre of Leksands-astrobleme
Pos. Ae	:	145546E/673655N	Hill Käringberget in Leksand
Pos. Af	:	145534E/673771N	Another tilted sheet N Käringberget
Pos. Ag	:	145944E/674009N	Amelioration cairn in S. Torrberg
Pos. Ah	:	145978E/674026N	Amelioration cairn in N. Torrberg
Pos. Ai	:	146970E/674090N	Pseudotachylites near Slättberg
Pos. Aj	:	146690E/674715N	Quarry at rim of the Leksand-astrobleme
Pos. Ak	:	147594E/676137N	Beach of lake Ljugaren
Pos. Al	:	149975E/676950N	Forest road from Svabensverk to Svartnäs
Pos. Am	:	145945E/672325N	South end of gravel pit at Gräv
Pos. An	:	146160E/675880N	Limestone quarry with vertical bedding

Pos. Ao	:	144370E/671720N	Tachylites in a fine-grained granite
Pos. Ap	:	140800E/670650N	Lake Hummeln, top of deforested area
Pos. Ar	:	146145E/675295N	Shore at the church of Rättvik
Pos. As	:	143143E/672829N	Gravel pit in Lake Stora Flaten astrobleme
Pos. At	:	143786E/673017N	Forest road north of Gäddtjärn
Pos. Au	:	143710E/672940N	Gravel pit near Gäddtjärn
Pos. Av	:	142210E/673090N	Shore of Lake Storflaten,west position
Pos. Aw	:	142250E/673075N	Shore of Lake Storflaten, east position
Pos. Aq	:	144660E/675475N	Pier at shore of Lake Sljan in Garsås
Pos. Ax	:	140830E/670625N	SW of road to Hummelsjön
Pos. Ay	:	146400E/678400N	Community of Furudal
Pos. Az	:	146540E/678130N	Centre of Oresjön
Pos. Ba	:	146835E/677900N	Centre of Södersjön
Pos. Bb	:	146540E/677928N	Amelioration cairns along carriageway
Pos. Bc	:	146750E/677940N	Granite ridge (eventually spall)
Pos. Bd	:	143639E/673074N	Samples to the west of this point
Pos. Be	:	140218E/670598N	Start of forest road to south
Pos. Bf	:	140195E/670595N	Crossroad
Pos. Bg	:	140182E/670500N	Cut through sand ridge
Pos. Bh	:	140223E/670346N	New forest road heading East
Pos. Bi	:	147260E/676240N	Start of forest road to (Pos. Bi)
Pos. Bk	:	138940E/679435N	Northern dam at Lake Kvien
Pos. Bl	:	143130E/672860N	East of Lorttjärnarna
Pos. Bm	:	144275E/671640N	South of Lake Gysjön