PICTURE OF A FROZEN INSTANT FROM THE BIRTH OF THE SILJAN-ASTROBLEME

Version 1.2.7

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Abstract

About 377 millions of years ago a series of meteorites, belonging to the same shower, fell in Sweden along a line from SW to NE with its centre at the present Lake Siljan in Dalecarlia. This fall has been described in /1/; there the coordinates of the minor astroblemes are given.
Depending on the different signs in nature several estimates for the outer diameter of the Siljan crater exist: Grieve/12/ estimated 52 km, Kenkmann and von Dalwigk/13/ estimated 65 km, Henkel and Aaro/14/ 75 km.
The Siljan-astrobleme is a complex astrobleme, containing a ring-dyke; shock-phenomena have occurred inside the ring dyke. In the following report below it will be shown how the diameter of an astrobleme can be determined: This author has studied, how far the shock front (boundary between un-shocked and shocked rock) has reached. This gives the true diameter. Because shocked material during the shock has very different mechanical properties than normal material, there is a visible boundary between these regions. Since the fall about 500 to 2000 m (uncertain figure) of the surface have been eroded away. We now see the boundary between shocked and un-shocked rock at that depth below the former surface. Outside this boundary there is the more or less visible outer crater. Its diameter is determined by how much rock has fallen down into the ring dyke since the impact.

During the flight through the atmosphere the later Siljan-meteorite has broken into several smaller and larger pieces. One piece landed very near to the larger Siljan-meteorite; this landing was near in space and near in time. Both astroblemes generated shock fronts that now (within the second of landing) approached one another and collided. In the collision region the smooth front of the Siljan astrobleme was deformed substantially. This is seen on a bathymetric map of the Lake Siljan. There is a bay (Österviken) along about 90° of the perimeter of the Leksands-astrobleme; on the diametric side there are no signs of a dyke. Therefore the estimate of the diameter of *this* astrobleme is more uncertain, it could be between 15 to 20 km.

Within the area of the Siljan-astrobleme there is an alochthone bar of paleozoic sedimentary rocks, 14 km long and 2 km wide. The simultaneous creation of the Siljan and the Leksand astrobleme is the vehicle that has transported this bar to its present position. A similar simultaneous landing of two meteorites near one another has recently been reported by Ormö et al /15/ for the 470 million years old Lockne crater in central Sweden.

Keywords: Siljan-astrobleme, Leksand-astrobleme, size of shocked area, complex astrobleme, ring dyke, Orsa-sandstone.

Introduction

Before the fall of the large Lake Siljan meteorite, 377 million years ago, the region round the later lake was covered by sediments from Ordovicium and Silurian, but not with Cambrian sediments, like in other parts of Sweden. The Ordovician sediments consist of reef-limestones and marl-limestones: The first have been and still are mined for production of CaO, the second ones for local burning of cement. The Silurian sediments are anaerobic black shales. Evidently this part of the country lay above Sea level at the time of meteorite fall. 120 km to the south round the city of Örebro, Cambrian and Ordovician sediments are lying in a basin created by a Precambrian meteorite /2/.

The fall of the Siljan meteorite has coated the circular area of the astrobleme with debris, created by the fall, and an unknown large area outside the astrobleme with debris, too. This area we do not know, since from that instant on erosion has removed a substantial thickness of sediments and bedrock: Thicknesses of 500 to 2000 m are mentioned in the literature /3, 4, and 5/. Today the Palaeozoic sediments are absent from the major part of central Dalecarlia, except some residues of the reef limestone at Våmhus, north of Orsa, north of Furudal and in the southeast at Blecket. In the region exists one additional sediment, too, from Lower Devon, called Orsa-sandstone: This will be dealt with later.

The Siljan-fall created an abnormal astrobleme, a so-called complex crater. There the central part of the ring is lifted up and the peripheral part depressed: A ring-dyke is formed. In this ring-dyke the Palaeozoic sediments have been preserved.

However, very particular circumstances have led to an abnormal appearance of the astrobleme: E.g. inside the otherwise bare Precambrian surface of the astrobleme there is a bar of carbonate stone, evidently thrown there. Near the village of Stumsnäs there is a limited region of Ordovician carbonate stone and at Osmundsberg the older reef carbonate is resting on the younger Orsa-sandstone.

To understand this will be the task of this paper.

Rocks belonging to this investigation

Like in chemical reactions nothing is lost during an impact and nothing is gained (besides the mass of the impactor), but there is a very substantial change in the mineralogy of some rocks.
In the initial situation the participating rocks in the Siljan-astrobleme had been (from upside down):

- Devonian sandstone: Because this stone mainly occurs near the town of Orsa this stone is called Orsa-sandstone.
  Here a very important mark has to be made: All evidence points towards that the very fine sand – forming the stone (particle-size 0,1 to 0,5 mm) – is the residue from the evaporated/fractured meteorite and the likewise evaporated/fractured rock at the impact site; the reasons for this opinion are given later down this paper.
- Silurian shale: This is a black shale, formed under anaerobic conditions that favoured formation of naphtha and methane. By exsolution balls of calcite have been formed inside the shale. Due to long-time pressure these balls have been changed to flat lenses.
- Ordovician limestones and reefs have been formed under oxidizing conditions. They contain the skeletons of several corals and the "bones" of orthoceratites and of trilobites.
- Bedrock of type Dalagranite and Igelbergsgranite. This is a granite that contains plenty of microcline, substantial quartz, less of albite, little of muscovite. Outside the astrobleme the microcline has the usual rose colour; inside (within the region that has experienced the shockfront) microcline is red to red-brown.

Different types of astroblemes

Depending on their mode of formation there exist two types of astroblemes: Simple ones and Complex ones. There is an enormous difference between these two; therefore they will be treated here below independently.

Simple astroblemes

When a smaller meteorite at relatively low speed hits the Earth surface it penetrates the surface and excavates a conical hole with a low angle. Generally these holes have a minor diameter of tens or hundreds of meters. The largest known one is the Meteorite Crater in Arizona, also called Barringer Crater; may be it was on the way to develop as an complex crater. In Estonia on the island of Ösel at the village Kaali there are 9 craters of this type within a very limited area. In Germany (in the state of Bavaria) near the lake Chiemsee a swarm of such water filled craters has recently been discovered; in the beginning they have been misinterpreted as bomb craters after the bombing of Munich during the Second World War. All these craters are young; older ones have been annihilated by weathering and erosion.

To avoid a misunderstanding: In regions that during the last hundred thousands of years had been covered by an ice sheet, but now are ice free, one can find a lot of such cones in former valleys – now filled up with glacial gravel – e.g. in Dalecarlia at Ingels (east of Lake Siljan) or west of Lake Flosjön at the village Sandvika. These are the residue of a large isolated iceblock, that has been wholly covered by the water born debris during the retreat of the ice front. Later in time the ice block has melted and the overlaying debris filled the hole: Here the angle of the conical hole is steeper and is determined by the slide-angel of the gravel.

Complex astroblemes

The size of the meteorite that had hit the former Siljan-region is estimated to be 1 to 2,5 km diameter (figures up to 5 km have been mentioned) and its speed 10 km/s. Such a large asteroid generates a complex crater. The characteristic of this is a central primary crater of 2 to 4 times the diameter of the meteorite and a depth smaller than its diameter. This crater rides on a cupola, coated with the residues of the ejected rocks from the primary crater. These contain in a very fine form the material of the meteorite itself and that from the svekofennian bedrock. From finds of rock samples we know that the temperature during the compression and evaporation of the primary crater has exceeded the evaporation point of iron, which is about 3000°C. This we know from fractions of the Orsa-sandstone, belonging to the sequence of involved Paleozoic rocks. Evidently the meteorite contained some metallic iron, too. This evaporated and the vapour coated nearby fractions of the dust-plume; the coating has been oxidized to hematite, a red oxide. After sedimentation from the dust-plum, by time the Orsa-sandstone had been formed. Such red sandstone occurs in large quantity here and there in the Orsa-sandstone (normally this is white, opaque). By using the microscope one sees the transparent quartz grains, coated with a red layer. That layer is easily dissolved in hydrochloric acid, which turns green from 2-valent iron and tells us, that the grains had been coated by iron-oxides. White, red, light brown fractions exist, with very sharp, irregular boundaries towards one another, created during a slide of the still unconsolidated sand. This is a convincing proof that the Orsa-sandstone has been created during and by the meteorite fall /8/.
Petalas /9/ gives a very complete description of all feasible properties and of the occurrence of the Orsa-sandstone, but without giving any explanation of its origin and formation.

Normal pressure waves – those that are created by e.g. an earthquake – propagate in the bedrock by the speed of sound in that rock. Here below some figures of the velocity of pressure waves in different media are given:

Air	0,33 km/s
Water	1,4 km/s
Aluminium	5,08 km/s
Steel	5,17 km/s
Limestone	3,5 to 6,5 km/s
Granite	4,6 to 7,0 km/s

If a meteorite hits the ground at lower speed than those above a simple astrobleme will develop. However, if its speed is above or far above those figures, a completely different physics takes over: A shock front starts to propagate at higher speed than the speed of the sound (not necessarily at the same speed as the intruder has) into the bedrock from the site of the impact. Normally meteorites have a limited size: At a larger distance from the impact point this front is a semi sphere. Sometimes the expression 'shock wave' is used: This is a misleading term, since behind the shock front (inside the spherical front) there is no oscillation of the pressure. The rock inside the semi sphere has now attained quite other physical properties: It is very ductile and behaves like a high-viscosity liquid. Above a critical pressure – different for different rock or metal – called Hugoniot elastic limit (after a French physicist, who has studied such exceptional properties) the shear stress $\tau = ½ \cdot Y$ is independent of the pressure, where Y = shear modulus of material in question. In other words: The solid material inside the 'bubble' has lost its normal rigidity and behaves like a superplastic. (For details see /11/, there Fig. 3.3 and Table 3.1). The Hugoniots elastic limit σ_{Hel} is in:

Halite	0,09 GPa
Vermont marble	0,9 GPa
Westerly granite	3 GPa
Lunar anorthosite	3,5 GPa
Armco steel	0,6 GPa

Back to our practical problem: Fig. 5.4 in /11/ shows the instantaneous pressure distribution during an impact. The isobars remind of the leaves of an onion; near the stem of the onion the isobars are very tight and disclose a high pressure gradient there. Probably the picture of a flat onion for the isobars is better than hemispheric isobars, at least when looking below the point of impact. There the static pressure is high due to the load of the superposed rock, which will hinder the propagation of the shock. Expressed with other words: In the Siljan astrobleme the shock front has a lateral spread of 18,5 km, but hardly such a high vertical spread. This figure 5.4 does not show, that the impactor during the ongoing impact is 'eaten up' by fracturing, melting and evaporation. These products are pressed out from the underside of the intruder toward the walls of the growing hole and blown up into the atmosphere. This process widens the initially cylindrical hole and the primary crater is formed. In the case of the Siljan meteorite fall the process of intrusion is estimated to have lasted 1 to 2 seconds.

The pressure in the superplastic bubble – particularly below the intruder – must have been very high. This leads to three effects:

- Near the primary crater rim the pressure gradient is high. Therefore sheets of the local rock have been lifted off and thrown away as 'spalls'. During their flight in the air these 'spalls' land at their normal (previous) orientation in space or they are turn around 180° and land on their back or at any other angle.
- Due to adiabatic heating (instantaneous heating due to pressure) and friction the temperature in the 'bubble' attained high values. This increases the pressure of the shock front on its surrounding additionally.
- The high pressure below the superplastic bubble – stored in the non-shocked bedrock - lifts the central part of the structure on expense of depletion of material within a ring-dyke around the primary crater.

The shock-phenomenon came to rest and ceased, when

- The propagation of the front had attained the local speed of sound,
- Or the source of the whole phenomenon – the meteorite – had been extinguished and thus all forces ceased.

After decompression the adiabatic temperature increase disappears equally fast like it increased on loading. However, the frictional increase in temperature disappears very slowly. The body of previously shocked rock shrinks and looses its contact with the surrounding non-shocked rock.

In a bowl without mechanical pressure on its surface the previously shocked (superplastic) material should shrink and form a large depression on its surface, like previously liquid wax that solidified in a pot. (The pot is the former last interface between the shocked and un-shocked rock). Its central part is still very hot and therefore plastic. Due to the pressure from beneath now this part starts to rise upwards: A central uplift is formed.
A good analogy of this process are slow-motion pictures of a water drop, hitting a water surface: The drop touches the surface, lifts to a 'central uplift' and a ring-dyke is formed.

During the first days after the impact this rise may have been quite fast. At the same pace as the temperature decreases also the rate of rise decreases. However, evidence from the field indicates, that the later rise was relatively low:

- For the first: Conduction of heat in a *solid* rock is very low. Cooling down from e.g. 1000°C may – depending on size - have taken thousands of years
- For the second: Samples from the *central* part of the astrobleme are completely depleted of free quartz. This quartz has been transported by the aid of steam upwards, is today seen as a network of overcrossing veins in samples from *peripheral* parts of the impact region

(An analogy to this phenomenon is the uplift of the Scandinavian shield after the loading during the latest ice-cover. To day the rate of rise at the most exposed site (at Höga Kusten at 63°N) is 9,2 mm/year.)

The summit of the central peak contains the primary crater. Just to get an estimate of what is possible: At the above speed it would take 100 000 years to reach a height of 1000 m. This is in geology a very short time span. *The material for the uplift has to be taken from the ring dyke, i.e. deepening it.*

There is another explanation of the formation of the central uplift:
Professor Melosh /11/, who without any doubt is an authority within the field of 'Impact Cratering', suggests that the rising of the central uplift of a complex crater starts within the short time-span of the very impact, during which the rock below the impact point is shocked (which means plasticised). The timescale for this rise is thus no longer than $(D/g)^{1/2}$; D = diameter of the complex crater (distance between diametral rims) and g = 9,80 m/s^2 the surface gravity constant.
In the case Siljan there is no distinct rim around the structure; however, the bathymetric maps of the lake show a ring-dyke with a diameter of 37 Km. This is quite certainly the diameter of the shocked volume at the present level (the impact hit a surface, which was about 500 to 2000 metres higher than the present one). If we use this figure, we would obtain a timescale of about 60 seconds.
At impact speeds of > 10 Km/s the very impact does not last many seconds: During this time a shock-pulse of very high pressure travels through the bedrock and heats it to temperatures above the melting temperature of the bedrock. This we know from the iron-coated ejected stone fragments, which later will render the Orsa sandstone. This heating is not only adiabatic (decreases immediately after release of the pressure), but also due to friction and therefore more or less permanent (decreases only by spreading over larger and larger volumes of rock). Therefore it is completely possible, that in this condition of the rock (melt or semi melt) the hole after the evaporated meteorite and its near environment is filled up by melt or semi melt rock from its more far surrounding. The clash of this streams in the centre will lead to an upwelling of that melted material to form a central uplift. Thus the former

crater has completely disappeared. The term 'melting' must not be overstressed: Here melting means a fluidisation of the shattered bedrock. A minor quantity of real melt, together with gas and water vapour is sufficient to give the damaged bedrock properties like a fluid.
A further consequence of this behaviour is the plane (horizontal) surface outside the central uplift, seen in so many lunar astroblemes.

Outside the primary crater most of the paleozoic sedimentary layers should have been preserved, since they are covered by the fall-out, which is the pulverized bedrock from the primary crater and from the pulverized and/or evaporated meteorite. This is the material, later on forming the so-called Orsa-sandstone.
Now the sandstone (to be) glides down on the Silurian shale into the dyke. The original stratigraphy (the youngest is up)

Orsa sandstone		Ordov. carbonate
Silurian slate	is thus reverted into	Silurian slate
Ordovician carbonate		Orsa-sandstone

Several slides in time after one another have thus formed the pattern of repeated layers sandstone – slate – carbonate, which are observed West of Mora.

There is another aspect of this model: In the East of the circle, formed by the dyke, the paleozoic sediments are not within the dyke, but some few kilometres to the West at Solberga, Boda and Osmundsberg. If the central uplift were not located exactly within the centre or steeper on its East side, this would explain this observation.

In the Siljan area the ring-dyke today is filled with water. Since the ring-dyke is not filled-up with sediments (see the bathymetric map) it is very probable that the water-filing occurred early and thus hindered the filling with sediments. During the many glaciations during the last 2 Million years it is most probable, that Siljan and other lakes here have been bottom frozen even a long time after recession of the ice-front. Thus there was no movement of the ice and its load along the bottom of the lake, not even during recession of the ice-front.
The diameter of the deepest circle around the astrobleme is the boundary between the two phases, unshocked rock (on the outside) and shocked rock (on the inside). This is the deepest circle within the dyke. This ring-dyke diameter of 37 km must not be confused with the diameter of the outer crater rim, which latter is determined by the mass, which has slid down. This interface should be visible in samples from core-drilling that penetrates this interface.

The Siljan-astrobleme is a complex astrobleme

The sketches Fig. 8 and Fig. 9 try to illustrate details of the Siljan-fall. The numbers in the sketches refer to the following list:

1. The meteorite was in the order of 1 or 2 kilometres across. Here it is show as a cylinder; a sphere is equally probable. It was a chondrite, containing some metallic iron, too (dyed the ejected dust).
2. After touch-down a shock front started from the meteorite into the base rock and another back within the meteorite. The upper remainder of the meteorite does not 'know', what is going on, proceeds at the original speed. The lower part of the impactor and the bedrock have started to evaporate, melt and are shattered to dust. A plume of dust originates from the interface between the meteorite and the bedrock.
3. The supersonic blow of vapour, melt droplets and mechanical dust widens the growing crater. Part of the dust is coated by the evaporated iron.
4. The primary crater is finished after 2 seconds. At its bottom there is some melt, consisting of matter from the meteorite and from the bed-rock. To the first approach the crater is a paraboloide; its diameter is estimated to be some few kilometres and its depth about one kilometre (these figures depend completely on the mass and the impact speed of the meteorite, figures we do not know).
5. Due to the back-fall from the plume of dust and due to sliding-down of the rim the crater widens to a modified primary crater.
6. Directly after touch-down a shock-front started to spread into the bedrock with a speed in the range of 10 km/s or more. The isobars of this process are at some distance from its origin hemispheres; all rock inside the surface of the - for the moment most distant isobar - is shocked, is in a plastic state and at a very high temperature, near the melting point of the rock. Depending on the local composition of the rock local melting there can happen. The high temperature has been established by adiabatic compression and by friction heat. The bubble of shocked rock creates elastic deformation and stress of the rock below it, which later will be used to lift the central part of the astrobleme (central uplift). The spreading of the outermost isobar ceases, when its speed gets identical with the local normal speed of sound.
7. Since in the figures (7) and (8) there is a gross difference between the horizontal and the vertical scale they have to be read with precaution. At the instant of fall of the Siljan meteorite for 377 million years ago, the ground has been at a higher level than to day. Figures of 0,5 to 2 km have been mentioned. Figure (7) is drawn under the assumption of 0,5 km of erosion since then. The previously shocked - but now un-shocked - rock is still very hot – near 1000°C. By the force of rebounce the primary crater will very soon be filled with hot rock. Therefore it is difficult to find residues

of the crater. Due to disorder between the grains, high temperature and exsolved gases the previously shocked ‘bubble’ of rock has certainly a lower density than the cold unaffected surrounding rock. Therefore this ‘bubble’ will float up; the deficit of rock will be made up by formation of a ring-dyke around the Central Uplift. In the beginning this process will be quite fast; later on – may be after ten thousands of years - the pace of raise will slow down. The sinking mass of rock in the ring-dyke helped to raise the central uplift. Now we have to look on figure (8): It shows the present state. The bathymetric map of Lake Siljan shows a 125 metres deep dyke round parts of the astrobleme (the other parts have been filled by glacial debris). This dyke has certainly at all time been filled with water: Erosion does not work in water at rest, nor does it deepen a pre-existing dyke. Therefore this dyke must have been established already in the beginning of the uplift. Its diameter is about 38 km, which is the diameter of the shocked rock ‘bubble’, which probably reached 19 km down. Erosion took place at the air-exposed free surface, not in water. It is more probable, that the dyke has been filled up by debris than that it had been deepened at the same pace as the rocks in free air. **The dyke is the boundary of the former astrobleme!** How high the Central Uplift once had been, we do not know. But certainly its rate of erosion had been higher than in the surrounding lowland.

Inside the ring dyke

Due to the general denudation by 0,5 to 2 km of the previous surface details of the primary crater have disappeared: We even do not know, where it has been. Going from the dyke towards the presumptive centre of the Siljan astrobleme, the - at several sites exposed bedrock (granite) - changes gradually. Unfortunately there are not very many outcrops of it, but the local till should be similar to the underlying rock. At the periphery (near the ring-dyke) the visible boulders are very rich in quartz, which in space forms a network of interconnected mm-thin fissures. The concentration of quartz there may be over 50%.
Towards the centre of the impact quartz gets more and more rare and disappears finally: The rock there should be called syenite. This is best seen in boulders, which contain melt, too. There is a mixture of “burned”granite and melt: The “granite” floats within the melt and is completely free from visible quartz.
Somewhere in-between the centre and the periphery there is a region of rocks, showing wide dykes of greenish quartz; the quartz here is microcrystalline. The green colour comes from dissolved epidote. Probably these dykes are not formed from quarts, dissolved in water vapour, but are the eutectic melt between quartz, epidote and water.
At the centre the dominating microcline is red to red-brown, is cracked and shows in the microscope tiny cracks, filled by a reddish melt. Only

large microcline crystals occur: Evidently these have been a long time near their melting point and have consumed all minor microcline crystals. Of course there is no quartz left in these stones.
Further near the periphery, e.g. at the shore at Garsås a strange rock is found: It is a granite. Containing the red-brown microcline, quartz and mica, but on its surface is rough, not polished nor rounded, like all other (transported) granite stones are. The same type of rock – belonging to the Floda-astrobleme - is found in dominating quantity at the saddle-point between the Alpine pastry Forsbodarna and Bodberget. This stone is quite fragile, breaks easily after a blow of the hammer. This author calls it *'reconstructed rock'*. It originates from the superplastic mass of the slurry of cracked crystals within the shocked material and has been 'glued together' by a melt phase. This phase is seen by microscope in many of the damaged crystals. Having in mind, that between the instant of impact and to day there was a denudation of 500 to 2000 m, not very much of the central uplift can be left. However, it still is visible: The village of Garsås and the flat 'inland' is about 80 m above the sea level.

Finally, where was the primary crater? This author started a search for it and believes that it is in Lake Icksjön or nearby to the west /7/. The reason for this statement is the following: At lake Icksjön only one type of rock is prevalent, viz. a quartz-free syenite; no other types of rock – local or transported there-to - are seen. From this it can be inferred that this lake is deep and during the melting phase of the last glaciations held a high ice-core, which prevented deposition of the stream load there. A deep lake may be the residue of the primary crater.

Another bewildering feature is a 2 km wide bar of Palaeozoic sediments, starting at Vikarbyn and pointing 45° up to east. This bar is definitely not autochthone, but has been moved to the present position and turned up 90°. On both sides of this bar carbonate rock exists and the central part is filled with Silurian shale. Several large quarries for limestone have been operated within this bar like: Amtjärn, Skålberg, Unskarsheden and Östbjörka on the bar's west side and Nittsjö and Kullsberg on its east side. The bar is 14 km long; at its upper end two lenses of late svekofennian granite are included which seem to originate from the nearby (6 km) village of Gärdsjö, outside the ring dyke. How this bar may have been moved to its present position will be discussed later in this paper.

The last strange feature is a field of limestone, about 8 km^2 size, below the village of Stumsnäs. This area is completely free from any outcrops with exception of a small quarry at the western border of that field. The only rocks found in the till are granites. Therefore this author believes, that this field is autochthone, and - due to the impact – had been covered by some other rock and thus preserved from erosion. Fig. 5 shows the bedrock of the whole Siljan-region.

Conservation of the Palaeozoic Sediment

Within the area above the ring-dyke

With only two exceptions (a small area 3 km west of Boda and Jälltjärnsberget NW of Osmundsberget) all Palaeozoic sediments are concentrated to the ring-dyke. The radial width can be quite large, e.g. at Mora 8 km, at Kallholn 9 km and at Furudal 8 km. Observed in radial direction: The visible layers are carbonate (Ordovicium) – shale (Silurian) – Orsa-sandstone (Oss)(Devonian) – shale(Sh) – carbonate(Ca). Fig. 6 shows, how the filling of the dyke may have happened. After sedimentation of may be 10 km^3 of blown-up fragments of the bedrock and of the very meteorite, the landscape must have been coated by a thick layer of sand (forming the future Orsa-sandstone). This sand on the Central Uplift easily moved by gravity or by rainwater into the nearby ring-dyke. Next the shale on top of the carbonate rock - due to its content of oil and mica - slides down and finally the carbonate comes. Therefore the present stratigraphy is inverted, compared with it after the original sedimentation.

There is one unsolved problem: Going from the inside of the astrobleme right to the west from Mora, the following sequence of sediments can be noted: Ca-Sh-Oss-Ca-Sh-Oss-Sh-Ca. Evidently two or more sheets from the Central Uplift have slid down after one another.

Within the circular area inside the ring dyke

There is a further unsolved question with name Solberga rev, Juttjärn and Osmundsberget: Between these quarries there are at least two more, which have the same peculiar properties. All these are lying in the wrong way: The (oldest) carbonate is lying on younger Silurian shale (Solberga rev) or in Osmundsberg carbonate on shale or carbonate on Orsa-sandstone.

If in Solberga the carbonate and the shale are lying in normal orientation (youngest layer up) they have reached this position by sliding down from the Central Uplift; however, if both layer are inverted, most probably they have been thrown there as 'spalls' from the rim of the primary crater. Therefore in this quarry naphtha is found in two boreholes down to the shale. The shale is fully visible in the western – lover - part of the quarry.

Spalls are relatively thin layers, originating from the rim of the primary crater. The force from downside, blowing the spalls up, is larger near the centre than further away from the centre: Therefore the spalls have the tendency to rotate during their flight.

Osmundsberg and Juttjärn are harder to understand. In its northern part of Osmundsberg carbonate rock rests on shale. But in its southern part the carbonate rests on Orsa-sandstone. Petalas /9/ reports several borehole logs on his Fig. 3D, from upside down: Juttjärnsquarry, core drilling 19/78: 117 m carbonate, 10 m shale, remainder Orsa-sandstone.

Osmundsberg, core drilling 4/69: 146 m carbonate, remainder Orsa-sandstone. Osmundsberg, core drilling, Stam 3: 98 m carbonate (3 m shale in-between), remainder red Orsa-sandstone.
The figures must not be over-interpreted: At Osmundsberg the original bedding of the sedimentation surface is everywhere tilted with a dip between 30 to 90°; therefore a vertical borehole will go at an oblique angle through the rock and make us believe a larger thickness of the bed than that really has.
When entering the Osmundsberg quarry – about 30 m from the pit – you see at the right side a vertical (former horizontal) carbonate surface, coated with thousands of 30 cm long 'tubes' in a statistical disorder. These 'tubes' are orthoceratites.

How could so much sandstone lie below the carbonate? A carbonate spall – even if it holds some shale, too, - is within seconds contemporary with the impact. The sand from the destroyed meteorite and the bedrock takes hours to come back. Therefore a spall cannot have fallen at the present site of Osmundsberg, but nearer to the centre. Professor Thorslund, the discoverer of the Siljan astrobleme, has recognised this and writes in an excursion guide /10/ on page 32: "Osmundsberget. A large hill formed by the Boda limestone and adjacent beds overthrust towards NW. According to drillings the thrust mass contains a lentil of Kullsberg limestone, and rests locally upon Orsa-sandstone ca. 70 m below the surface of the hill." Thorslund gives no explanation what this thrust could have been.

Note, that the series of quarries from Solberga to the north does not lie on the ring-dyke, but several kilometres to the west. From Bysjön (1 km north of Osmudsberg) travels a depression with a brook right to the north into Ore lake. On the northern side of this lake this depression continues to the north as Ore River; this depression continues until the boundary of Dalecarlia. The depression seems to be a natural boundary between svekofennian granite in the west and migmatite in the east.

'Spalls' are generated almost immediately with the impact and are often turned at an angle to the horizontal site of landing; slides from the central uplift retain their orientation from sedimentation. Thus determination of what originally is "up" is of vital importance in reconstructing the history of the impact.
There is one additional late force, that might move large blocks of rock: It is the force of the moving ice during glaciation periods. It could even push spalls up the hill. From study of land movement by ice we know that this happened at the island of Mön in Denmark and at the island of Rügen in Germany. In both cases the advancing ice front lifted moraine and chalk to 80 m above present Sea level.

What does the bathymetric map of Lake Siljan tell us?

Since 2012 there exists a bathymetric map of Lake Siljan and of the Orsa-lake; this author received it first in September 2014: Immediately it gave answers to up to date open questions. Excerpts of this map are given in two figures /6/: Fig. 3: Northern part of Lake Siljan and Orsa-lake and Fig. 4: Lake Siljan between Garsås beach and Rättvik. The Orsa-lake is omitted here, but the map shows the upper continuation of the deep trench, like in Lake Siljan. The largest depth there is 94 m.

One of the questions was the correct diameter of the Lake Siljan ring dyke. Fig. 4 shows a deep trench starting in Orsa-lake, passing under the town of Mora and passing by the island Sollerön. In the Orsa-lake the trench is 94 m deep; due to enormous inflow of sediments from the river Österdals-älven it disappears at Mora. Only a few kilometres south of Mora the depth is again 98 m. Between Sollerön and the opposite Yrjasvik a depth of 125 m is reached. Looking on the isohypses these show a gradient of more than 45°. Sediments, deposited at the floor of the lake during multiple Ice-ages, hide that the real depth may be even larger. The absolute level of Lake Siljan is at 161 m above Sea level. This gives the level of the bottom of the dyke at 36 m. SW of Tingsnäs-udden the depth of the trench is 134 m which is only 27 m above Sea level. Nowhere in Dalecarlia region such absolute level exist; having in mind that the dyke is partly filled up by younger sediments, its real depth may have been at ±0 meters above Sea Level.
Having in mind that the land surface at the instant of the meteorite fall has been 500 to 2000 meters higher than to day, the initial depth of the ring-dyke must have been between 600 to 2100 meters. Today this would have been the deepest ravine on Earth.
The above facts are so interesting and – to this authors knowledge - have not been shown anywhere in European astroblemes, that two projects are suggested here:

- From the Swedish Navy hire an unmanned research vessel with remote crew to make many photographs of the bottom of the Lake Siljan dykes. Probably there will be large boulders from the flanks of the dykes, but also Orsa-sand (note: not Orsa-sandstone). It is highly improbable, that the water-impregnated sand has sintered to a stone.
- If possible, make a core drilling at the deepest point of the dyke, suitably during winter, from a raft on ice. This could disclose, how deep the dyke is.

The eastern side of the Siljan ring is higher than the western side: From about 200 m in the West to 380 m east of Boda. Therefore no branch of Lake Siljan exists there. However, deep below Boda there are two connected lakes, the northern and the southern Lake Ockran; these are in

a deep trench at a height of 213 m above sea. The slopes of the trench have about the same gradient as those on the diametrical side of Lake Siljan. How deep the Ockran lakes are we do not know. It seems evident that these lakes are the eastern ring-dyke of the Siljan astrobleme. These two observations give a diameter of 37 km for the ring-dyke.
It is worth noting, that the high region between Boda and the Ockran lakes is free from Palaeozoic sediments; due its height it may have been free at all times.
After several Ice ages there are no or few Quaternary sediments at the level of the Ockran lakes. This is astonishing, since the main flow of the melt-water stream during the retreat of the last glaciation at about 9800 BP (now the present river Ore Älv) passed this valley on its way to the south. Today Ore Älv has from Lake Ore taken another way to Lake Orsa. The explanation of the missing Quaternary deposits is the following: On that occasion the surrounding hills had been ice-free, but not the valleys. Above the Ockran lakes the stream flowed upon the ice sheet, filling the valley, and the stream-load had been deposited further to the south, starting at the southern end of the southern Lake Ockran. When finally the ice-front reached the Ockran lakes, there had been no load left in the stream. Today these lakes dewater to the north!

A further observation should be mentioned: Evidently the depression of the ring-dyke had been filled with water at an early time and is filled until now. Otherwise it should have been filled with younger sediments that initially must have occurred richly. Note the filling of the ring-dyke at the location of the town Mora by sediments, delivered by the Österdalsälven.

Following the ring dyke southwards to “Cape Stumsnäs” the dyke has changed its expected shape from a banana to a S-form. West of Stumsnäs there is a mass of sunken rock at less than 10 m depth, in direct contact with a 134 m deep ravine. This latter makes a loop first to the north, later on to southeast, into the narrow bay for Leksand. The S-structure looks as if “Cape Tällberg” has been moved to the west and pressed the ‘banana’ together. Much points towards that this is the correct description! See next Chapter!

The Leksand astrobleme

Yes, there exists a Leksand astrobleme! Its diameter is about 15 km and its centre lies south of Lindberg. The ring dyke belonging to it, passes the bay of Rättvik and the bay for Leksand (max depth 102 m); there is no further part of the ring dyke visible. However, there are other proofs. Near the town of Leksand is the hill Käringberget at (Pos. Ae); this is a flat rock dipping at about 45°from a height of 240 m into the bay at 161 m. At its western side there is an extended layer of quartz along which the rock once had broken from its previous bedding. The east side is covered with soil, it is the former vertical break surface. Some 300 m to the north

there is a similar risen-up rock at (Pos. Af). Also Storön (an island in Byrviken, a bay belonging to the Leksand bay) is a spall. It is about 25 m high and has a vertical break at its south side.
However – if the above should not be enough evidence - there exists a convincing proof for a Leksand-astrobleme in shape of a large active quarry for macadam at (Pos. Aj). There the rocks have no names, since they are a mixture of other – previous – rocks, which have been redone by the impact. At an earlier stage of quarrying one could find there the remainders of the Silurian shale in the shape of a chlorite stone. The quarry is 2 km NW of the village Mårtanberg.
In the bay of Rättvik there are two different indications for parts of two ring dykes (see the bathymetric map of Lake Siljan), the one belonging to Lake Siljan, the other to the Leksand astrobleme. Since sediments from several consecutive glaciations have filled up this bay, the dykes are not so deep as the others in Lake Siljan.

The outfow from Lake Siljan is the bay 'Österviken', which at the town of Leksand goes over into the river Österdaläven; this bay is about 20 km long and 1 to 2 km wide. At its deepest point it is 102 m deep. This point is at about (160 – 102) = 58 meters above Sea level. The local erosion base is the now drowned rapids at Gagnefs Gråda at about 165 m above Sea level (number uncertain within ±2 m). No river erodes its bed below its local erosion base: In this case the outflow from Lake Siljan should have eroded its bed to (165 – 58) = 107 meters below its erosion base. This is impossible, which shows, that the 'Österviken' bay cannot be a river outflow, but is the outer dyke of the Leksand-astrobleme.

The story of the bar from Vikarbyn to Östbjörka

Starting with the information the bathymetric map of Lake Siljan gives, an attempt to reconstruct the whole story of the strange bar from Vikarbyn to Östbjörka is following here; it sounds crazy, but is the only one this author can device. Also the "Double Arch natural bridges" in Utah (USA) look crazy, but they stand, where they are:

In the west part of the bar of Palaeozoic sediments from Vikarbyn to Östbjörka the reef carbonate at Amtjärn quarry and Skålberget are standing vertically; in the east part (Unkarsheden and Kullsberg) they have a dip to NW; this simulates a larger cross-area than their real area is. Without any doubt the bar which is alochthone, has been thrown to its present position; all explanations must contain this fact.

Why is the Leksand astrobleme so interesting? Because it shows an extremely rare situation, where two parts of the same meteorite have landed very near one another with – estimated – less than one second time delay. When the later Siljan-meteorite 377 million years ago approached the Earth from SW, it broke up in the atmosphere and formed

a shower of minor meteorites from Äppelbo in SW to Lake Balungen in NE. About eight to ten larger and smaller impacts are known, e.g. that north of Dala-Järna, forming the lakes Stor-Flaten and Stora Snesen.
Smaller fragments of the main meteorite sense a relatively larger flight-resistance and land therefore nearer the break-up point. The Siljan-meteorite has separated from the Leksand-meteorite quite late, therefore these two have landed so near to one another, near in space and near in time.
Due to its size the Siljan meteorite should have landed somewhat earlier, may be less than a second earlier. Immediately after 'touch down' a shock-front started to spread in the solid ground from each impact site in all directions, also along the line between the two centres. The front from the Siljan-impact had a longer way to travel than that from the Leksand impact. The pressure fronts met somewhere in the bay of Rättvik. This must have been a clash never experienced on Earth!
The pressure could only be relieved upwards. Somewhere along this clash a bar of rock, a 14 km long and 2 km wide spall, consisting of the sediments carbonate stone and shale, lifted and had been thrown to the north, forming the peculiar strip from Vikarbyn till Östbjörka. Also some of the bedrock followed in this trip. The spall may have originated in the strip from the present bay west of Rättvik to the lake Ensen. The hole it left has some hours later been filled by air-borne sediment, giving the later Orsa-sandstone.

The peculiar orientation of the sediments in the bar in relation to one another is more difficult to understand: The western part of the bar now stands right up (the bedding surfaces of the carbonate rock are now vertical) and the carbonate is on the outside of the strip. The same is true for the eastern part of the bar: Even there the carbonates are at the outside of the bar. From the spall named "Solberga rev" we know, that spalls may travel a substantial distance and may turn around by 180° before landing. So, why not even 270°?
Now we are looking along the bar to be, from SW to NE: Along a strip – some hundreds of meters wide - the surface of the earth, above the meeting shock fronts, bulged up and broke at the crest of the bulge. Each part of the bulge flows up and rotated along its length, but in opposite direction: The left part rotated counter-clockwise, the right part clockwise. At the same time they had an impulse to fly to the NW. Hardly the whole length of 14 km they flew as a solid piece, but more probably broke up in smaller ones. Just at their landing these pieces had rotated around 270°. Now the shale-sides of the two half-bars pointed towards one another, much of the shale fell down and filled up the gap between the two vertical bars of reef carbonate. The right bar took with it some of the bedrock (svekofennian granite), too. The whole process must have happened seconds after 'touch down'.

Due to denudation up to date, the up-risen bar had been eroded to the level of its surroundings. The edge of the Unkarsheden-quarry (to day Dalhalla) is at 230 m above Sea and the quarries depth is about 30 m: There was no further reef carbonate, to be quarried. The following sketch Fig. 7 shows the above description.
If somebody could show that there is a measurable orientation within the originally horizontal reef carbonate and find this 'arrow' in the to-day vertical reefs Skålberget (lies on the west side of the strip) and from Nittsjö or Kullsberg (lies on the eastern side), these two arrows should point in opposite directions.

Conclusion

In this paper this author has tried to collect the existing knowledge on the "landing" of the Siljan meteorite and added knew extrapolated knowledge, extrapolated from a new bathymetric map of the Lake Siljan:

- The Lake Siljan is a so-called complex astrobleme with a circular dyke just inside the outer crater wall. This is a better measure of the diameter of the astrobleme than the diameter of the outer crater, which can have slid more or less into the dyke. The dyke-diameter is 37 km. The deepest depth of the dyke is 134 m.
- The sand for the later Orsa-sandstone originates from the impact itself. It consists of the fragmented and partly evaporated meteorite and of the fragmented bedrock. In its purist form it is white, but may be red and brown, too. In the red form the grains are coated with an evaporated layer of iron – now transformed to hematite. Iron evaporates first above 3000°C, which on Earth is achieved in astroblemes, only. See /8/.
- Due to erosion during 377 million years the position of the primary crater has disappeared. However, there exists evidence from the field, that Lake Icksjön in the centre of the astrobleme is the locus of the primary crater /7/.
- On its way through the Earth's atmosphere the Siljan meteorite fractured into several smaller meteorites: One of these is the so-called Leksand-meteorite, which landed simultaneously with the Siljan meteorite at such a distance, that the corresponding ring-dykes almost touch one another. This fact led to a displacement of the Siljan ring-dyke to an S-shape, instead of a smooth 'banana'. The Leksand-meteorite is responsible for the long bay N of Leksand.
- Starting from Vikarbyn in SW there goes a 2 km vide and 14 km long bar of Palaeozoic sediments in NE-direction up to Östbjörka. This bar is alochthone, has been cast to its present position by the collision of the two shock-fronts. Details of this process are given in this report.

About the author

The author is physicist (PhD) from the University at Stuttgart and geologist (fil cand) from Uppsala Universitet.

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Positions

Pos. Ae	145546E/673655N	Hill Käringberget in Leksand
Pos. Af	145534E/673771N	Another tilted sheet north of Käringberget
Pos. Aj	146690E/674715N	Quarry wihin the Leksand-astrobleme

Photos, maps and sketches

Fig. 1 Red and white Orsa-sandstone. Note the uneven contact between the two types (IMG_2752)

Fig. 2 Orsa sandstone from quarry at Kalmora. Note three different colours and (in the brown part) intercalated flakes of Silurian shale (IMG_2011)

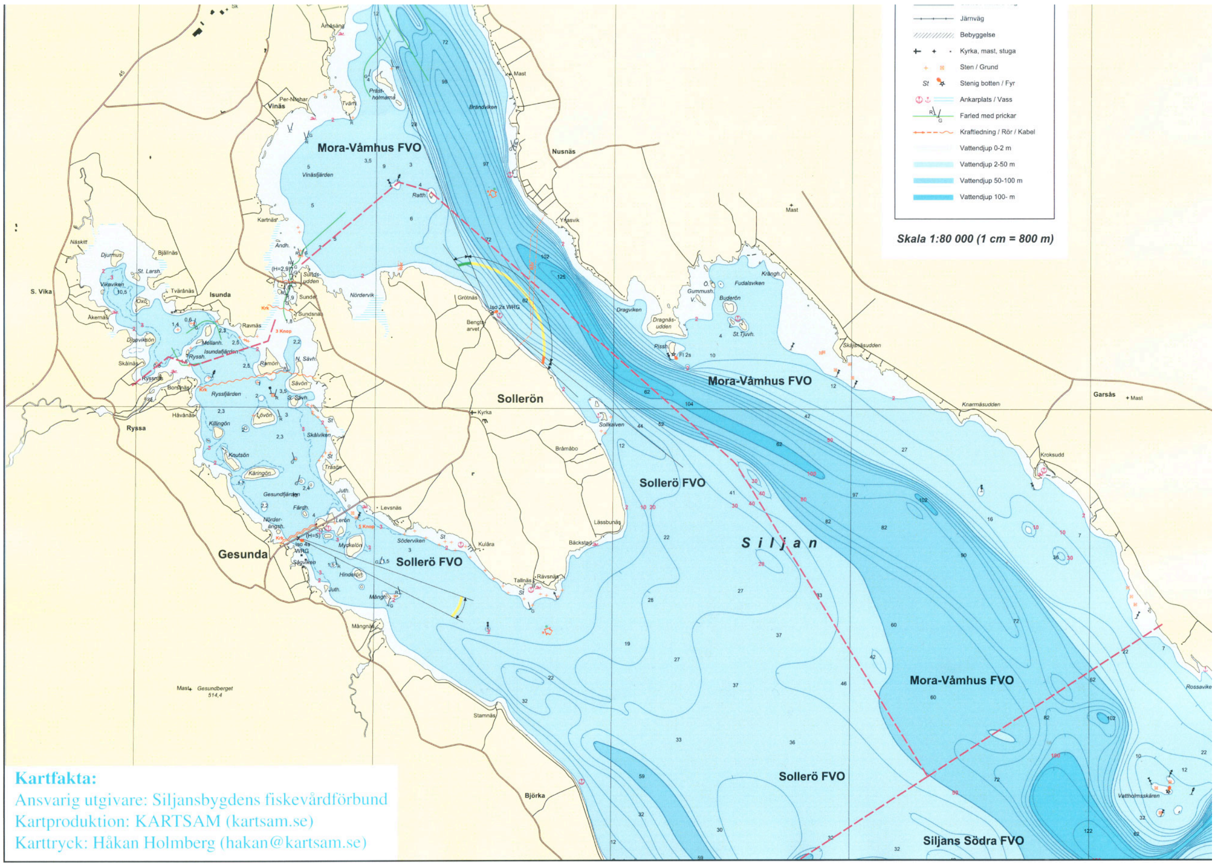

Fig. 3 Bathymetric map of the northern part of Lake Siljan

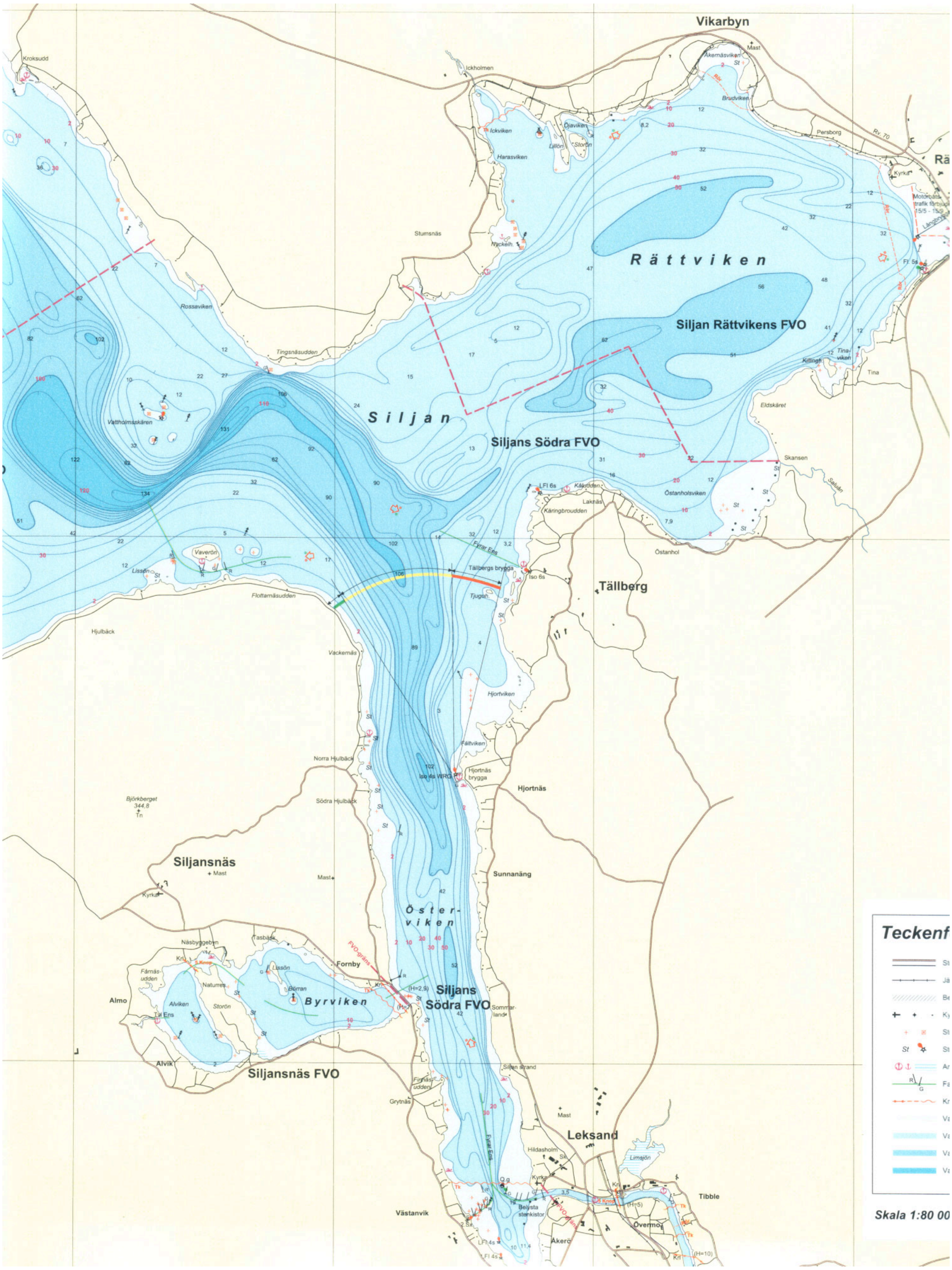

Fig. 4 Bathymetric map of the southern part of Lake Siljan

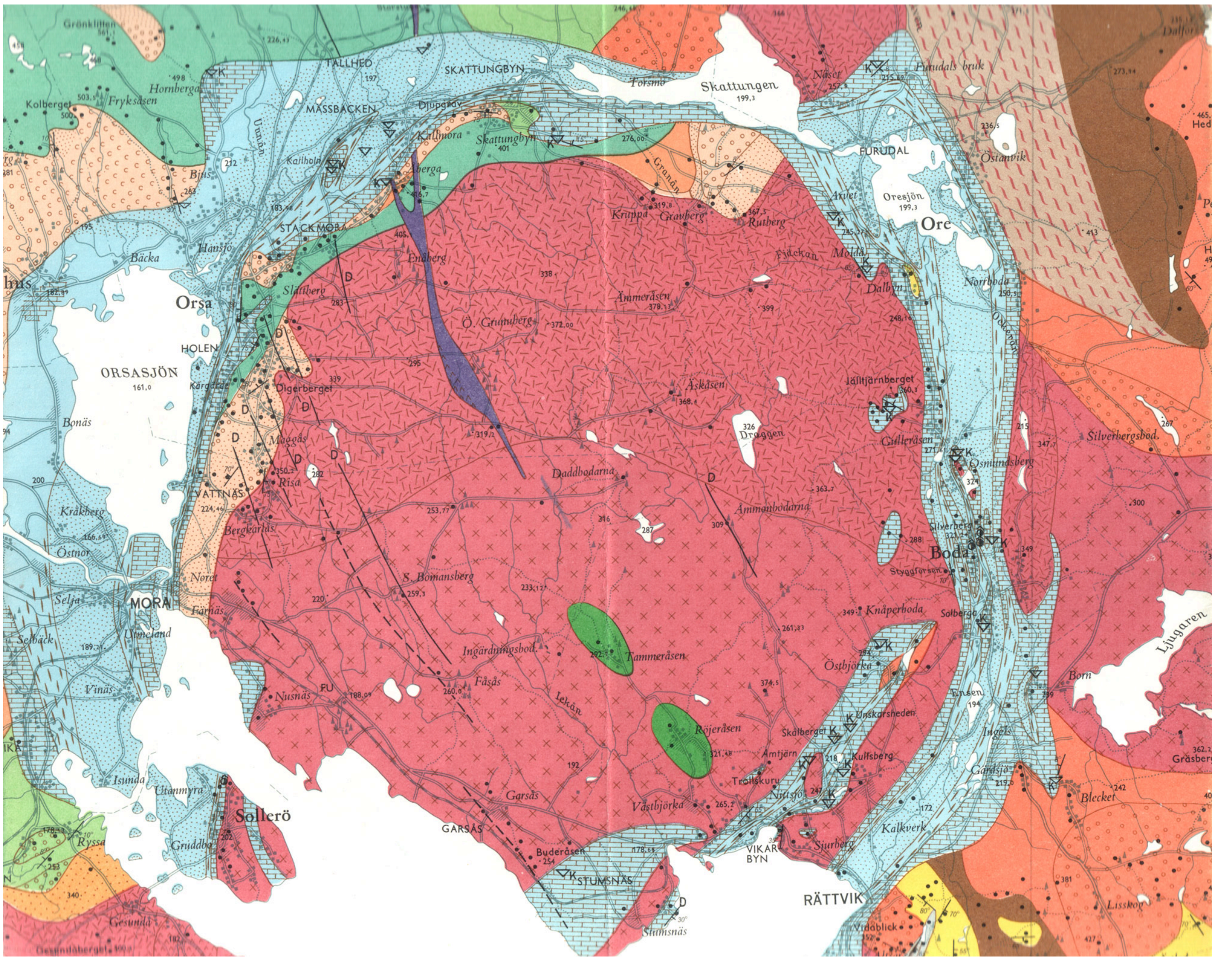

Fig. 5 Geologic map of the Siljan region, taken from the mapp: SGU Ser.Ca Nr 40: Berggrundskarta Kopparbergs Län, Scala 1: 200 000, Norra bladet

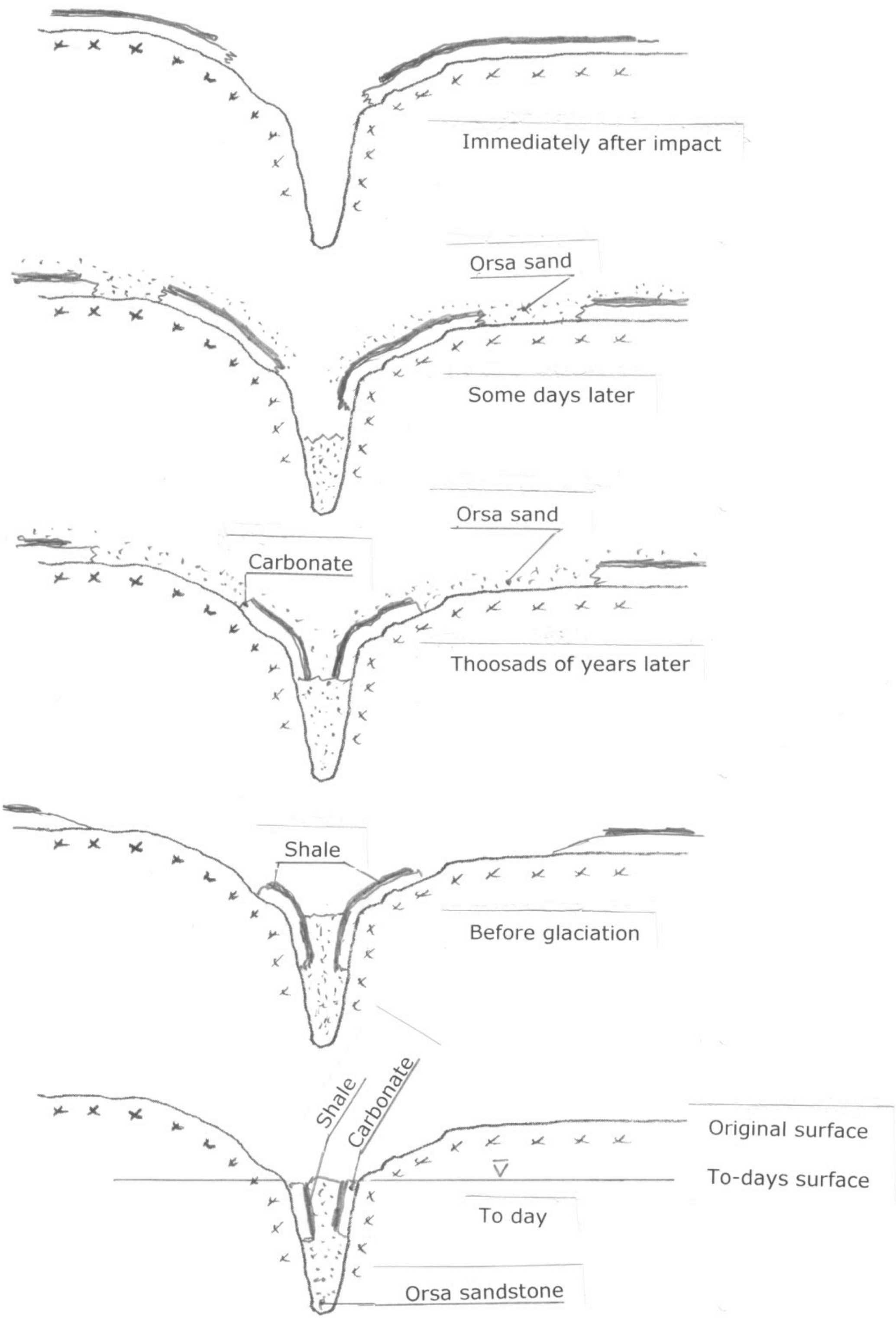

Fig. 6: Development in time of filling of ring dike

Fig. 6 Sketch of filling of the ring-dyke by sediments

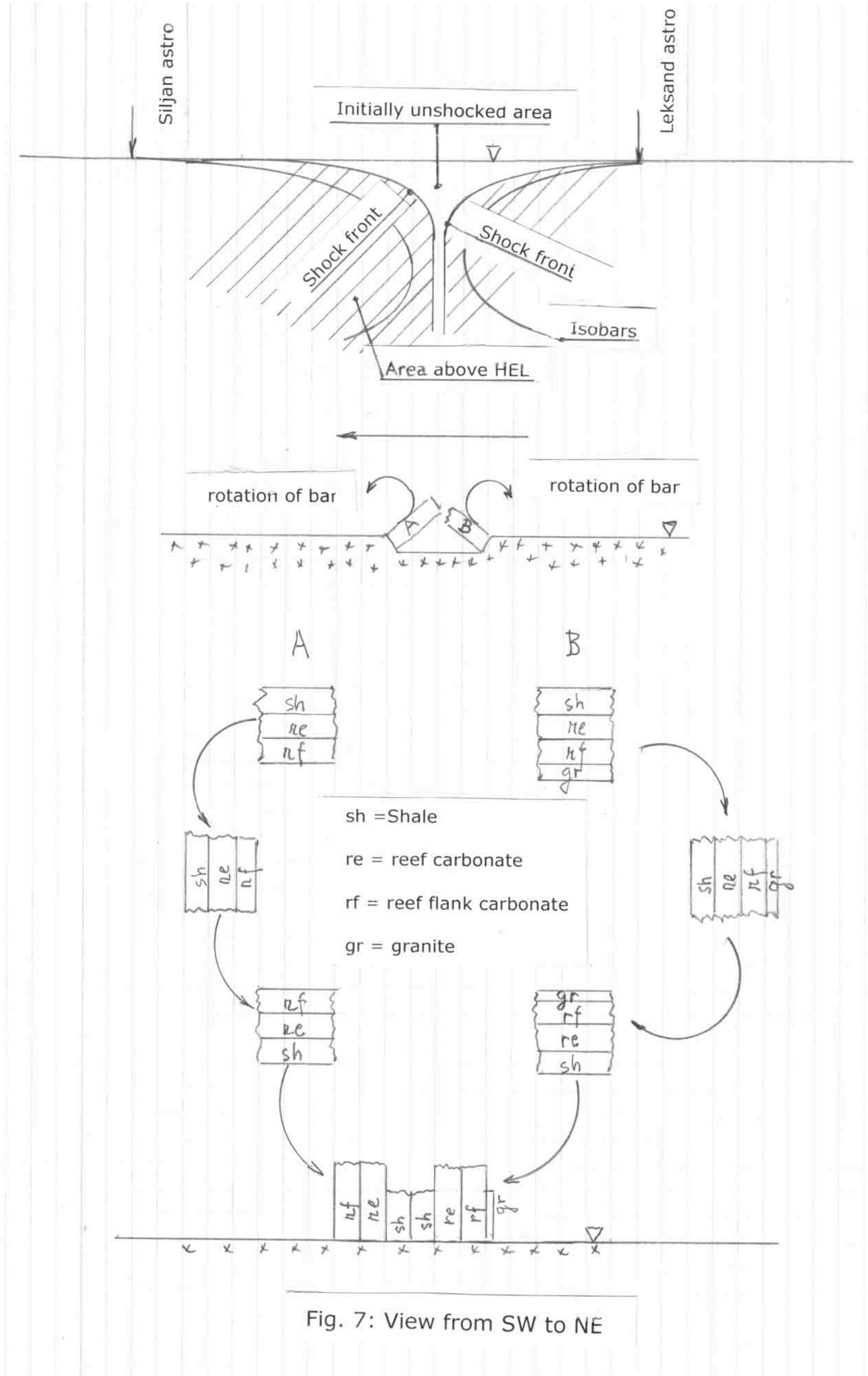

Fig. 7 Sketch of the transport of the bar from Vikarbyn to Östanbjörka

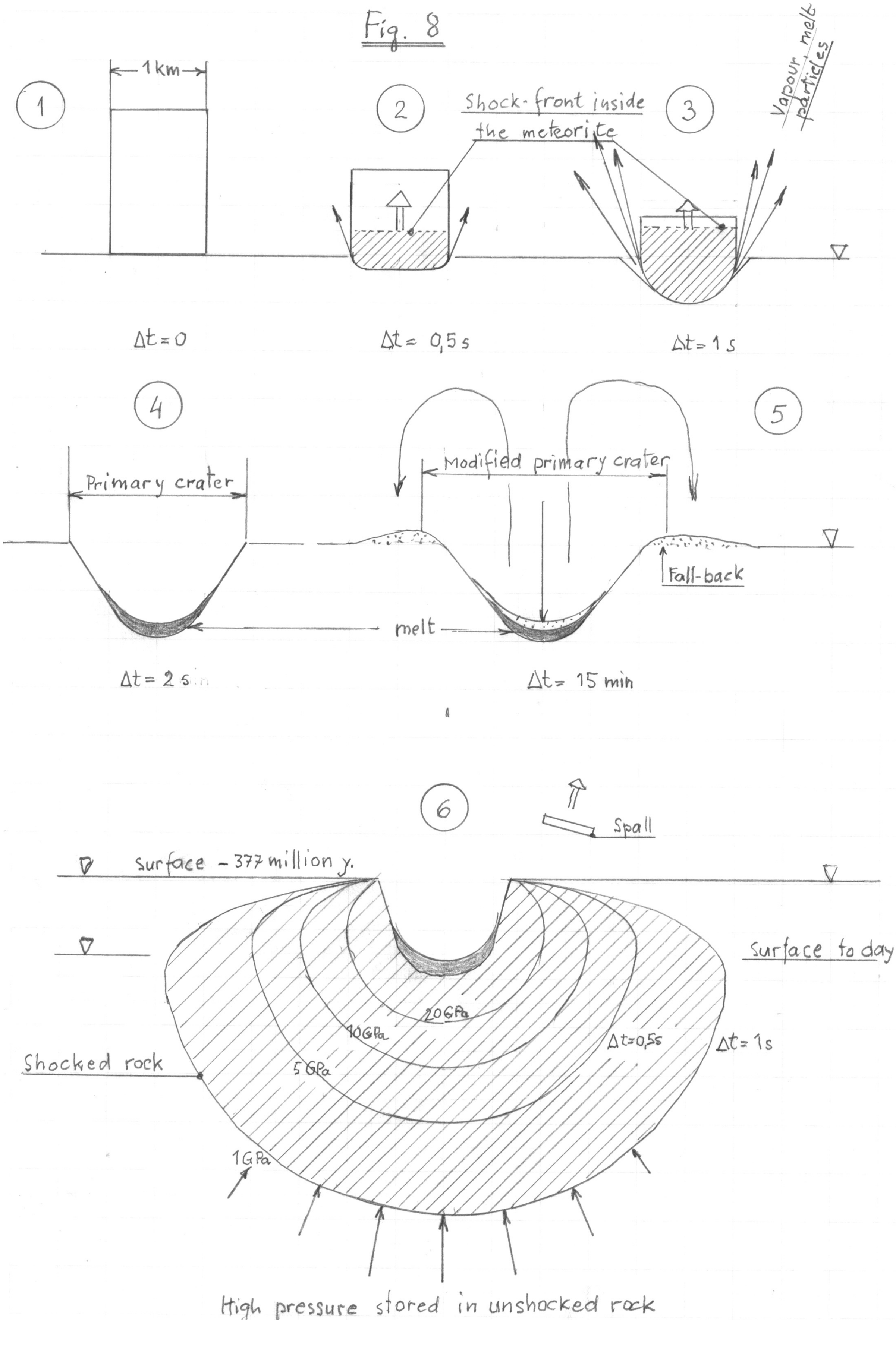
Fig. 8
1
1 km
Δt = 0
2
Shock-front inside the meteorite
Δt = 0,5 s
3
Vapour, melt particles
Δt = 1 s
4
Primary crater
melt
Δt = 2 s
5
Modified primary crater
Fall-back
Δt = 15 min
6
Spall
surface - 377 million y.
surface to day
20GPa
10GPa
5 GPa
1GPa
Δt=0,5s
Δt = 1s
Shocked rock
High pressure stored in unshocked rock

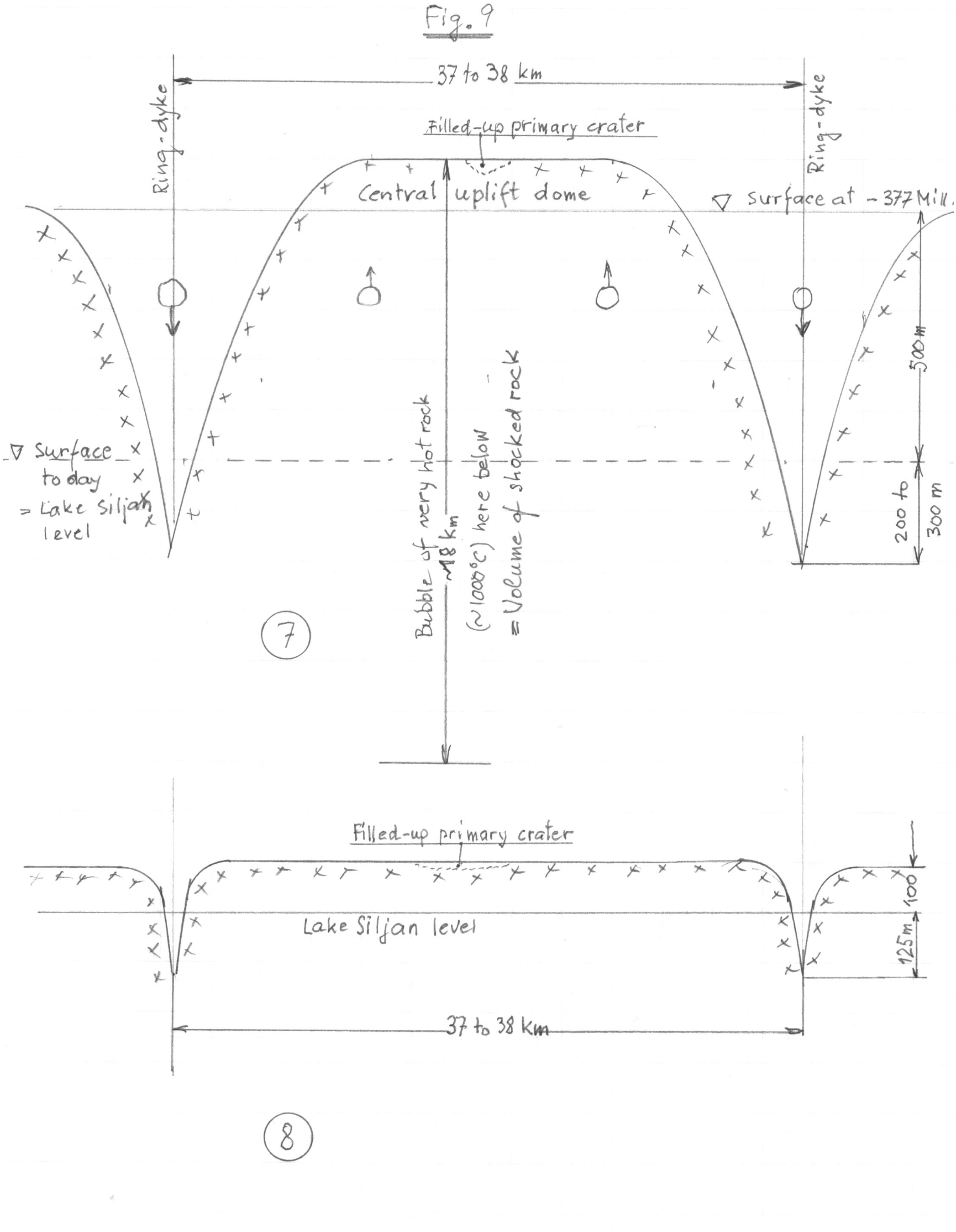

Fig. 9
37 to 38 km
Ring-dyke
Ring-dyke
Filled-up primary crater
Central uplift dome
Surface at -377 Mill.
500 m
200 to 300 m
Surface to day = Lake Siljan level
Bubble of very hot rock (~1000°C) here below = Volume of shocked rock
18 km
7
Filled-up primary crater
Lake Siljan level
100
125 m
37 to 38 km
8