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Clast analysis of potential resurge deposits as part of the Vakkejokk Breccia in the Torneträsk area, northern Sweden - a proposed impact ejecta layer

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ABSTRACT

In the northern part of Swedish Caledonides, north of Lake Torneträsk is a 7 km long exposure of a breccia layer. The layer thins westwards and eastwards from the central part where it is up to 27 m thick. It is called the Vakkejokk Breccia after the type section. The breccia has been described in literature since about a century, but its origin is enigmatic. The breccia layer is since the summer of 2012 investigated by three geologists specialized in impact craters, Paleozoic sediments, and the Caledonian orogeny. They put forward evidence for the breccia being formed by a hypervelocity impact during the Lower Cambrian at approximately 520 Ma (Ormö et al. 2017). At that time the target area was a shallow epicontinental sea that surrounded the mainly peneplanized continent Baltica. An impact into the sea is known to generate tsunami waves as well as resurge deposits when the water brings ejected and rip-up material back into the crater. Ormö et al. (2017) suggest the top part of the Vakkejokk Breccia to include such resurge deposits. The depositional marine environment is also known to rapidly protect an impact crater from further erosion. It is possible that only the topographic rim of the Vakkejokk crater was eroded during the millions of years it may have taken before the crater was covered by younger sediments. About 100 m.y. after the formation, it was completely covered by overthrust nappes during the Caledonian orogeny, when Baltica and Laurentia collided. The crater itself is not exposed today, merely parts of what is thought to be the ejecta layer and resurge deposits. This Bachelor of Science project aimed to investigate the putative resurge deposits to learn more about the process of formation and the provenance in the target of the clasts in the deposits. This was carried out by three short drillcores through the resurge deposit part of the Vakkejokk Breccia layer. The place to drill the boreholes was chosen at an outcrop which is proximal to the putative hidden crater. The retrieved drillcores were cut longitudinally, then polished and photographed in high resolution. Each core was then analyzed in an image analysis software with respect to clast granulometry and lithology. To the results are presented as graphs showing clast size, size sorting, clast shape, of the relative amounts of different lithologies and the matrix content. The results are discussed with respect to well-documented analogue marine-target craters

Front cover: Vaivvancohkka - Salmmecohkat massif photographed from a helicopter cockpit. The mountain nearset photographer is Mount Vaivvancohkka's southern side. Behind is Mount Balggescohkka, Mount Salmmecohkat, Mount Duoptecohkka, Mount Rivgooaivi with more aforementioned mountains. The Vakkejokk Breccia layer is outcropping along the foot of the southern facing massif, especially Vaivvancohkka. Photography: P. Minde 2016.

GLOSSARY

Breccia: Blatt et al. (2006) explain it as “Any rock consisting of large angular fragments (clasts), mostly applied to sedimentary and volcanic rocks and to material deformed by brittle failure in fault zones”.

Chert: Blatt et al. (2006) describe chert as a “rock composed of microcrystalline quartz of subsequent habit, typically with a diameter less than 20μm”.

Conglomerate: Blatt et al. (2006) describe conglomerate as “a coarse grained clastic rock composed of rounded gravel.

Hypervelocity impact: Hypervelocity impact occurs when a cosmic projectile is large enough (typically >50 m for a stony object and >20 m for an iron body) to pass through the atmosphere on Earth with little or no deceleration and so strike at virtually its original cosmic velocity (>11 km s^{-1}; French, 1998). This produces high-pressure shock waves in the target. Smaller projectiles loose most of their original kinetic energy in the atmosphereand produce small metre-size ‘penetration craters’, without the production of shock waves as cited in Osinski & Pierazzo (2012).

Impact breccia: Osinski & Pierazzo (2012) describe this as “a monomict or polymict breccia, which occurs around, inside and below impact craters”.

Impact crater: Osinski & Pierazzo (2012) describe it as a “generally circular crater formed either by impact of an interplanetary body (projectile) on a planetary surface or by an experimental hypervelocity impact of a projectile into solid matter. Applicable for fresh craters; for eroded craters, the term *impact structure* should be used”.

Impact ejecta blanket: Osinski & Pierazzo (2012) describe this as “a continuous ejecta deposit around an impact crater”.

Impact ejecta, ballistic: Osinski & Pierazzo (2012) describe it as a “solid, liquid and vaporized rock, or any combination thereof, ejected ballistically from an impact crater.

Impact ejecta, proximal: Osinski & Pierazzo (2012) describe this “impact ejecta deposited within five crater radii of the impact point.

Impact melt-bearing breccia: Osinski & Pierazzo (2012) describe this as “a impact breccia with a clastic matrix containing lithic and mineral clasts in various stages of shock metamorphism and including clasts of impact melt that are in a glassy or crystallized state”.

Impactite: Osinski & Pierazzo (2012) describe this as “rocks affected by impact metamorphism (includes shocked rocks, impact breccias and impact melt rocks”.

Orogeny: “A mountain-building event” as cited in Marshak (2011).

Planar deformation features: Is described by Osinski & Pierazzo (2012) as “submicroscopic amorphous lamellae occurring in shocked minerals as multiple sets of planar lamellae (optical discontinuities under the petrographic microscope) parallel to rational crystallographic planes; indicative of shock metamorphism”.

Sorting: According to Blatt et al. (2006) sorting is “The selection during transport of particles according to their size, specific gravities, and shapes. Well sorted sediment has only a small amount of variability among the diameters of its particle”.

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1. Introduction

Within the Torneträsk area in northern Swedish Lapland (figure 1), is the 180 meter deep, approximately 10 km wide and about 70 km long Lake Torneträsk (Vogel et al. 2013). The lake is situated in a NW–SE trending depression, which is formed by repeated glaciations during the Pleistocene (Stroeven et al. 2002). On the northern side of Torneträsk is a group of connected mountains, which form the Vaivvancohkka – Salmmecohkkat massif. According to Kathol (1986) and Lindström (1987) the massif consists of easterly transported, now westward slightly dipping stacked thrust sheets underlain by the pre-Caledonian autochtonous sedimentary succession of the Dividal Group, deposited unconformable on the Precambrian basement. The Dividal Group crops out as a sinuous, eroded belt along the border of the Vaivvancohkka – Salmmecohkkat massif (Kathol 1986, Thelander 1982; Lindström 1987). On the northern side of Torneträsk depression; close to the S-W corner of Vaivvancohkka – Salmmecohkkat massif is Mount Vaivvancohkka that reaches almost 1000 meters above the surface of Torneträsk. The peak of Vaivvancohkka consists of a very low grade meta-sedimentary sequence intruded by sub-parallel, discordant dolerite dykes (Kathol 1989). On the southern facing side of Vaivvancohkka, about 500 meters below the peak is a scarp, which consists of a thrust sheet of Precambrian cataclastic felsic igneous rocks (Kulling 1960). The scarp runs about 15 km to the ESE and E (Kulling 1960). The scarp is by Sami people called Vaivanlåpme (Viklund 1910). Along the foot of Vaivanlåpme is the 170 meter thick Dividal Group that in turn is intercalated in its lowest part by a conspicuous coarse, polymict breccia called Vakkejokk Breccia (Kulling 1964, Thelander 1982; Lindström 1987). The breccia layer is up to 27 meter thick (Ormö et al. 2017); and extends narrowly all the way in the same stratigraphic position along the foot of Vaivnlåpme for a distance of about seven kilometers between the rivulets Vakkejokk (today Orddajohka) in the west until Tjärurajokk in the east (Kulling 1964; Thelander 1982). The section between the two rivulets is by Ormö et al. (2017) called the Vaivvancohkka section. The type section where the unit for the first time was scientifically described is located at the rivulet Orddajohka, formerly Vakkejokk, which is the reason the breccia is by Kulling (1930) called the Vakkejokkbreccia, and later the unit name Vakkejokk Breccia by Thelander (1982).

According to Ormö et al. (2017) the breccia layer reaches a maximum thickness of 27 meter slightly to the west of the central part of the Vaivvancohkka section, and it then thinning west- and eastwards. They further state that the breccia layer is generally well exposed and often seen as prominent terrace. For some stretches the layer is covered by Quaternary deposits, scree of fallen rocks and dense mountain forest. The Vakkejokk Breccia has been regarded an anomaly since its discovery and it has been investigated by numerous geologists who has proposed various causes for its genesis; disputed ideas such as tectonic-breccia, glacial till deposit of lower Cambrian or Neoproterozoic ice ages, gradual mass wasting slope processes related to freeze-thaw activity, solifluction processes, till that has running embedded in a glacier, a deposit due to massflow caused by soil-flow, or a deposit due to rockslide combined with subsequent sub-aquatic slump (Kulling 1930, 1951, 1964, 1972; Strömberg 1981; Thelander 1982; Stodt 1987; Lindström 1987; Romer & Bax 1992). Recent interpretation by Nielsen & Schovsbo (2011) and Ormö et al. (2017) is that the Vakkejokk Breccia is an impact breccia layer or an impactite, which was formed by a hypervelocity meteorite impact. The breccia would thus belong to an ejecta blanket relatively close to the putative crater. They infer that the breccia has an absolute age of ≈520 Ma. The location of the putative crater is still not known, but is suggested to be below Vaivvancohkka. Ormö et al. (2017) divide the Vakkejokk Breccia into four sub units; (1) the lower unit is interpreted as ballistic ejecta i.e. "bombardment of the nearby sediment immediately at time of impact"; (2 & 3) two normal graded units, which are suggested to be resurge deposits; and (4 unit) a <30cm thick conglomerate at top that is suggested to be related to the degradation of the crater rim. Alwmark et al. (2016) and Ormö et al. (2017) report finds of shocked quartz from the Vaivvancohkka section as well as from two distal sandstone beds.

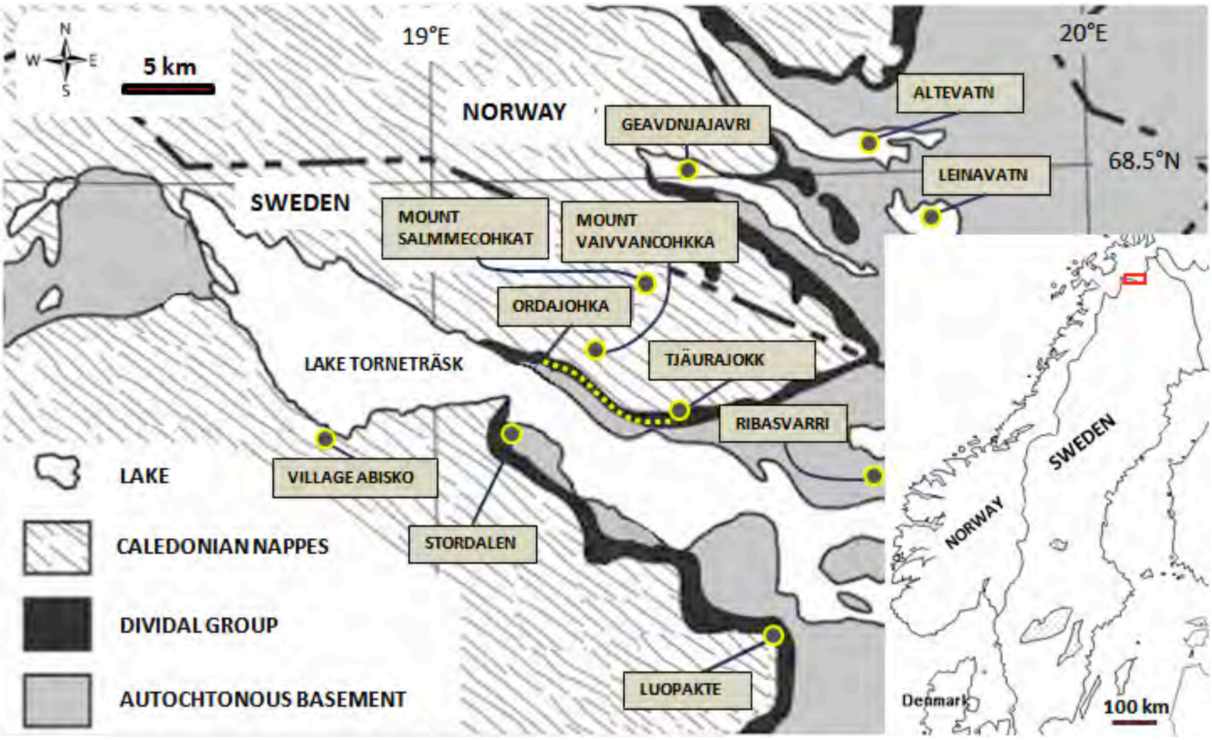

Figure 1. Simplified map of the geography, geology and spatial relationship between autochthonous basement, Dividal Group and the overthrust Caledonian nappes at Torneträsk area, the red rectangle at the inset indicates the Torneträsk area. The Dividal Group outcrops sinuously along the eastern border of the northern part of the Swedish Caledonides. The mountain area north of Torneträsk is in this thesis referred to as the Vaivvancohkka - Salmmecohkat massif. Between Orddajohka and Tjäurajokk is the Vakkejokk Breccia layer (indicated by a yellow dotted line). Figure is modified from Rehnström & Torsvik (2003, Fig. 1A)

1.1. Aim of the study

This bachelor's thesis focuses on the sedimentology of the Vakkejokk Breccia. It will provide relatively detailed relationship between the subunits of the Vakkejokk Breccia, with special emphasis on the uppermost, proposed resurge deposits. Of interest was to examine if the transition between the Top Sandstone and the underlying Graded Polymict Breccia has a sharp or a transitional boundary, which both varieties are seen at Lockne (figure 2), as well as get more information on the transition from the Lower Polymict Breccia, that underlies the Graded Polymict Breccia. The results will improve the understanding of the resurge dynamics in general.

2. Geology of the research area

2.1. The lower Cambrian

This thesis follows the stratigraphic nomenclature of the Torneträsk Formation in the Luopaktee area by Nielsen & Schovsbo (2011, fig. 42). The stratigraphy is limited to the four lowermost units of the Torneträsk Formation of direct relevance to the studied breccia layer. Three of them are informal members and the fourth i.e. the Vakkejokk Breccia is a formal member (Thelander 1982). Further in text the first letter of all words used in the names of formal lithostratigraphic units is capitalized.

According to the Geological Survey of Sweden's Bedrock map sheet 30J NW Rensjön by Kathol & Martinsson (1999); Thelander (2009) and Nielsen & Schovsbo (2011) the autochthonous succession in the study area belongs to the approximately 172 meter thick, Dividal Group from Cambrian time, which comprises the Torneträsk Formation, and the overlying Grammajukku and Alum Shale Formations. Of interest for this study is only the early Cambrian Torneträsk Formation, which in general varies from silt to sand implying an inner shelf environment that during a generally (although with brief fluctuations) continuous transgression is changing to an outer shelf environment after the time of the putative impact (see discussion in Ormö et al. 2017). The lower Cambrian Torneträsk Formation is 80 meter thick is divided into four parts by Nielsen & Schovsbo (2011); the lowermost part is the up to eight meter thick, informal Lower Sandstone Member, which rest unconformable on the basement. The Lower Sandstone Member consist of conglomerate, feldspathic sandstone and sandstone rich in quartz, with local inter-beds of fine-grained sandstone and fine grained siltstone. According to Thelander (1982) and Stodt (1987) the contact between basement and the overlying Lower Sandstone Member is marked by the occurrence of bottom conglomerate of varying thickness, which contains mostly rounded quartz pebbles and, at some places, a residual remnant of weathered basement. Vogt (1967; post mortem publication, the original studies was done in 1915) report in a profile south of Geavdnjajavri a circa six meter deep weathered basement overlain by a bottom conglomerate; in addition he report that south of Geavdnjajavri a 11.5 meter thick layer of (Nowegian: grønn skiefer), e.g. "green siltstone" in Vogt's unit B e.g. the "Lower Siltstone Member of Thelander (1982)". Vogt's unit B has a stratigraphic position according to Nielsen & Schovsbo (2011, fig. 47) below the Vakkejokk Breccia. The Lower Sandstone Member shows a gradual transition into the overlying 18 meter thick, informal Lower Siltstone Member (Nielsen & Schovsbo 2011, fig.42), which consists of sandstone and siltstone. According to Jensen and Grant (1998) the Lower Sandstone Member is unfossiliferous and the lower part of the Lower Siltstone Member contains only undiagnostic trace fossils. Kulling (1972); Stodt (1987, p.71) and Jensen & Grant (1998) reports the trace fossil *Kullinga concentria* in a siltstone bed between two and four meters below the top of Lower Siltstone Member. The Lower Siltstone Member is overlain by the informal Red and Green Siltstone Member, which is 22 meter thick at Mount Mount Luopaktee (see Nielsen & Schovsbo 2011, fig.42); which in turn is overlain by the circa 34 meter thick, informal Upper Sandstone Member. The Vakkejokk Breccia has a stratigraphic position within the Lower Siltstone Member.

2.2. Proterozoic basement

According to Bedrock map sheet 30J Rensjön NW by Kathol & Martinsson (1999) the Proterozoic crystalline basement at Torneträsk area is 1.8-1.9 Ma and belongs to the Svecokarelian orogeny. As seen on the bedrock map it consists mostly of the Lina granite Suit, although other minor units and groups are present (Kurravaara Group, Haparanda suit and Perthite-Monzonite suite). According to Kathol & Martinsson (1999) the Proterozoic basement of the Perthite-Monzonite suite extends along the Norwegian border. The Perthite-Monzonite suite's southern contact is to the Lina granite suite. The Perthite-Monzonite and Lina granite suite seem to underlay the Vaivvanchokka – Salmmecohkka massif. The Haparanda suit which appears at the Torneträsk area consists of diorite and gabbro, which appear as "numerous small bodies" Kathol & Martinsson (1999). According to Martinsson et al. (1999) the Kurravaara Group consists of conglomerates in a matrix of volcanic ash (tephra) along with intermediate meta-volcanics seen in the area at Lake Ripaisenjärvi (about 13 km east of Tjäurajokk). North of Torneträsk is an approximately 20 x 13 km wide Lina granite intrusion, which is intensely injected by aplite and pegmatite dykes in a 2 to 4 km wide zone in its southern part The Lina granite suite north of Torneträsk is according to Martinsson et al. (1999, p.73) medium to coarse grained and partly contains phenocrysts of ~10 mm large microcline. About 16 km east of Tjäurajokk at Mount Ripasvarri fragments of diorite, intermediate meta-volcanics is present and up to some meters thick pegmatite and leptite veins (Kathol & Martinsson 1999). From the Lake Altevatn and Lake Leinavatn area (i.e. the next lake east of Lake Geavdnjajavri) Slagstad et al. (2015) report small, scattered, weathered outcrops of plutonic gabbro. Slagstad et al. (2015) further infer from the extent of a high aeromagnetic anomaly that the plutonic gabbro probably extends southwards below and beyond Leinavatn. In general the gabbro is coarse grained and it varies in outcrop from light colored (leuco) gabbro to olivine 2-pyroxene dark colored (mela) gabbro, olivine and apatite is present in a few samples (Slagstad et al. 2015). According to Bergman et al. (2001) and Hallberg et al. (2012) as cited in Slagstad et al. (2015, p. 448) the Kiruna Greenstone Group comprises greenstone, commonly graphite bearing meta-mudstone, and ultramafic rock, crystalline carbonate rock and sedimentary chert. Lundqvist (1953) reports that the basement in the area north of Torneträsk consists of pink reddish medium grained late Svecokarelian granite and migmatite-gneiss and that the basement is "very monotonous". On the southern side of Torneträsk from Luopaktee to Stordalen the bedrock described by Holmqvist (1910) and Ödman (1957) in Lindström et al. (1985) remark that red potash-rich granites and hornblende-rich syenite with gabbroidal inclusions are the primarily rocks of the basement. In a reconnaissance survey Pettersen (1887, p. 423) reports that the basement in the vicinity of Orto-jokki e.g. "Orddajohka" consists of red medium to coarse grained granite, which complies with (Kathol 1989) who reports that the basement underlain the Vaivvancohkka – Salmmecohkat massif consists of medium to coarse grained granite. A study by Witshard (1984, p. 294) reports that the Torneträsk area has a granitic basement and that the Lina granite suit has widespread occurrence of pegmatoidal zones and pegmatites, which are absent in the Pertite-Monzonite suit. The basement between rivulet Orddajohka and Tjäurajokk is reported by Kulling (1930) to consist mainly of Proterozoic fine grained felsic granulite, red-gray granite and granite-gneiss.

2.3. Earlier works

Pettersen (1887) reported from the Orddajohka rivulet in the late 18th century a conglomerate containing fragments of the Laurentic derived rocks in a bed of moderate thickness. According to Kulling (1930, 1960) the Vakkejokk Breccia was first described scientifically in the summer of 1930 during a regional survey by the Geological Survey of Sweden. Kulling (1960) report that the contact between the granitic basement and the overlying bottom conglomerate is visible about 330 meters north of the mouth of rivulet Orddajohka and that the bottom conglomerate is in turn overlain by sandstone, and, further on, siltstone. Intercalated within this siltstone, at a small waterfall about 700 hundred meter north along the rivulet, Kulling (1930) reports a conspicuous polymict breccia layer; allegedly about 12 meter thick. The thickness at the waterfall is revised to seven meter by Kulling (1964), which is closer to the thickness later stated to 3-4 m (Thelander 1982) and the 5 meter estimated by Ormö et al. (2017). According to Kulling (1964) the Vakkejokk Breccia layer extends in more or less in the same stratigraphic position 7 km but could be seen as thin layer at least 14 km along the Caledonian eastern margin of from Orddajohka in the eastern direction along to Vaivvancohkka – Salmmecohkat massif. Ormö et al. (2017) has estimated the thickness of the layer to ≤ 27 meter.

2.4. Various causes for breccia genesis

According to Kulling (1930) the Vakkejokk Breccia at Orddajohk shows a matrix that consists of shale and the clasts in the breccia are mainly more or less red-gray syenite-granulites, e.g. "fine grained felsic rocks of Kulling (1930)" and numerous pieces of green-gray siltstone of the lower Cambrian sediments; one or other percent is fine-grained red-gray quartzite-limestone, dolomite (beef-red); coarse grained dolomite, gray limestone, fine grained schist. Kulling (1930) discusses that the red-gray quartzite-limestone, red-limestone and the fine grained schist is not known from the Cambrian sediments and that they most likely represent some formation older than the lower Cambrian. He also argues that the Vakkejokk Breccia has a tectonic origin from the time of the Caledonian orogeny. At the type-locality at rivulet Orddajohka the boundary between the breccia and the substratum is pseudoconformable and undulating (Kulling 1960).

Kulling (1951) discusses that the Vakkejokk Breccia has similarities with tillites and may belong to the tillite formations in northern Norway, i.e. from the Varangian Glaciation. However, Kulling (1964) concludes that while the Vakkejokk Breccia resembles a tillite, it has also several features which do not match a tillite, such as different sections are composed of diverse types of breccia i.e. variations of Vakkejokk Breccia both laterally and horizontally. Kulling (1964) observed and interpreted that the Vakkejokk Breccia and Lower Sandstone Member have similarities with sediments that are deposited at time of sea level rise and he discusses the possibility that a monadnock "inselberg" stood over the general level of the surrounding area during transgression of the sea. From such an inselberg an extensive rock slide could have occurred, and let rock rush down into the littoral zone of the surrounding sea. The rock that rushed down caused a sub-aquatic rock slide (a submarine slump) and subsequent mud rushes; in which boulders and mud were mixed up together. Lindström (1987) describes how the breccia contains huge slabs of basement granite entrained in surging mud, which originates from dislodgement of a massflow. Kulling (1964) has also considered the possibility that the Vakkejokk Breccia may originate as a flow-till that was deposited into the sea, and later lithified. Kulling (1964), Strand and Kulling (1972) and Thelander (1982) describe how most of the clasts are granitic and seem to originate from the Proterozoic basement, that two other clast types are sandstone and shale, the latter often transformed into matrix, and that clasts in the breccia vary from angular to well rounded, some with the clast size ranging from small grains up to slabs of several hundred meters in length.

Kulling (1972) and Strömberg (1981) discusses that the Vakkejokk Breccia originates from gradual mass wasting solifluction slope processes with related to semi-frozen ground e.g. “freeze-thaw activity and peri-glacial climate” based on its composition such as boulder, clay, and presence of laminated siltstone which is not associated with glacial moraines. Thelander (1982) observes that boulders and other dense material seem to have sunk down into the underlying sediments as indicated by soft sedimentary deformation, which would indicate that deposition of the breccia happened before the sediment was lithified. Thelander (1982) and mentions that fine-grained greenstone and mafic clasts are found sparsely in the breccia. Ormö et al (2017) report about fragments o a red lithology in breccia at Orddajohka.

Stodt (1987, p. 51) argues that the Vakkejokk Breccia originates from N-S striking faults causing uplift of a paleotopographic high with resulting mass flows during collapse of the high. Stodt (1987) divided the Vakkejokk Breccia into four types D, C, B, A. The lowermost type-D contains 2-100 meter large granitic basement-derived blocks, which are lying on top of, or embedded in, disturbed and folded siltstone, or on type-C breccia. Type-C breccia has a red, green, or gray silty to sandy matrix, is clast-supported, and with clasts having nearly the same dimensions, sometimes slightly stretched or internally brecciated. More than 90% of the clasts are granitic, the rest mainly randomly oriented and contorted sedimentary clasts. The granitic clasts are sometimes well-rounded, but for the most part angular. The type-B breccia reported by Stodt (1987) is a sandstone bed up to 0.3 m thick, which sometimes shows normal grading. The bed contains clasts which are granitic, vein-quartz, silt and shale of up to some cm-size, bladed and discoid clasts are oriented parallel to bedding, and joined with a carbonate cement that seems be derived from carbonate mud. Type-A breccia categorized by Stodt (1987) is interpreted as a probable mid-fan deposit, and is described from a locality about two km south-east of the Norwegian rivulet Aldasjohka i.e. on the south side of Geavdnjajvri. He report that it occurs one meter below the top of the Lower Siltstone Member and that at the base there is a 0.12 meter thick conglomerate bed with up to 4 cm large, well rounded dark siltstone clasts and a few made up of vein-quartz. The bed is said to show the sedimentary Bouma-T_{ABCD} sequence, i.e., sediments deposited by turbidity flows.

The massflow hypothesis by Kulling (1964) and Stodt (1987) is supported by Romer & Bax (1992) in their view that the Vakkejokk and (Holmajärvi-diamictite) are fault related and are located where old fault zones (N-S to 20E and NW-SE) transect the Proterozoic basement. The Holmajärvi diamictite-conglomerate has a polymict, gray-green matrix described by Ödman (1957, p. 107-108) who interpret it as an Eocambrian tillite, however with the reservation that it could be Postcambrian fault-related diamictite. Stodt et al. (2011) argue that the peri-glacial hypothesis is unlikely in view of the paleolatitude of S30–50° during deposition of the Vakkejokk Breccia.

2.5. Distal counterparts to Vakkejokk Breccia

A possible counterpart to the Vakkejokk Breccia in the same stratigraphic position as the Vakkejokk Breccia occurs at Luopaktee (Kulling 1964; Strand and Kulling 1972; Thelander 1982). At Luopaktee, in the uppermost part of the Lower Siltstone Member is a 1.67 m thick layer of dolomite-sandstone containing feldspathic sandstone with a 0.5 meter thick basal conglomerate, which contains small clasts of Proterozoic granite, vein-quartz and greenish siltstone with barite crystals (Kulling 1964; 1972); as Nielsen & Schovsbo (2011) the conglomerate layer estimated to 0.2 meter thick. Føyn (1967, p. 36), when referring to the report by Vogt (1967, p. 55), mentions a peculiar 0.3 m thick conglomerate bed with a strongly yellowish coating atop unit C e.g. "atop Lower Siltstone Member of Thelander (1982)" from a locality in northern Norway, Vogt (1967) discuss that it could be a counterpart to Vakkejokk Breccia. Holmquist (1903) mentions briefly a sediment breccia on a small hill at Stordalen with a stratigraphic position just above the bottom conglomerate.

3. Relevant features of marine-target impact craters

To date there are 190 confirmed impact structures published in the Earth Impact database (*http://www.passc.net/EarthImpactDatabase/*) of which eight are located in Sweden. Still, on the Earth, hundreds of impact structures are still awaiting to be found (French 1998). As nearly ¾ of the Earth for most of its geological history has been covered by water means that an equal amount of the impacts would have occurred at sea (Ormö & Lindström 2000).
Most of the hypervelocity meteorite impacts have an oblique angle when striking the ground, most commonly 45°. Craters formed at this impact angle are still circular in outline, but the ejecta blanket may become irregular. The speed of a meteor is commonly 20 km/s when entering Earth's atmosphere, but may vary between 11-72 km/s (French 1998). The formation of an impact crater is a complex process, and for convenience it is common to separate the processes into three stages. Each of these three stages is dominated by different forces and mechanisms. The first stage is the contact and compression stage when the projectile unloads its kinetic energy into the target; the second is the excavation stage when the crater expand by material ejection and displacement; and the third is the modification stage when the excavation of the crater has ended and the last ejecta fall back to the ground while material is sliding back into the crater (Melosh 1989). There are two lines of evidence that can be used to prove an impact origin of a suspected crater or lithologies; shock metamorphic features and meteoritic material (e.g., French 1998). The shock metamorphic effects must be above pressures that may occur at endogenic processes in the Earth's crust. The observed features can be macroscopic, i.e. so-called shatter cones, or planar deformation features (PDFs) or high-pressure polymorphs of minerals (e.g. coesite, stishovite). The most commonly used are the PDFs, which are parallel planes through the crystal, usually quartz, where the crystal structure has been destroyed along certain directions with respect to the crystal's C-axis (e.g., Ferriere et al. 2009). The meteoritic material also occur as macroscopic pieces, but due to the often near complete melting and vaporization of the projectile in impacts it is more common

with a contamination caused by certain elements (e.g. iridium) that are rare in the Earth’s crust but less rare in asteroids (e.g., French and Koeberl 2010).

A hypervelocity meteorite impact into a sea is known to generate tsunami waves as well as resurge deposits when the water brings ejected and rip-up material back into the crater. The definition and general description of resurge as given by Ormö et al. (2007) is as follows: “The principal material evidence of a resurge at an impact crater confirmed to have formed in a marine environment (i.e. showing continuous marine sedimentation before and after the impact) consists of a fining-upwards succession of clastic sediment that can be extremely coarse in its basal parts and ends upwards as fine sand to silt at its top. The bulk composition of this deposit is the same from bottom to top, although there may be variations in detail. This succession is the product of erosion and deposition connected with the collapse of the transient crater in the water causing a return of water to the crater excavated in the rocky target i.e. (the seabed).” The totality of this process is by Ormö et al. (2007; 2017) called the “resurge” and its products "resurge sediments or resurge deposits" although it includes important outward water and debris movements that may dominate in late stages.

Given the marine sedimentary target sequence, and the potential water reworking of parts of the Vakkejokk Breccia, it is reasonable to assume that the putative impact occurred in a marine environment (Ormö et al. 2017). Hence, some of the typical features of marine-target craters, the formation of resurge deposits, and one of the closest analogue craters are here briefly reviewed. The Lockne crater (63°00’ N, 14°49’ E) in Jämtland is today the northernmost Swedish proven impact structure. This crater formed 458 Ma, but is remarkably well preserved and well exposed. Likewise, decades of studies has rendered it one of the most well documented craters on Earth. Lockne is a rare example of an impact into a 500 meter deep epicontinental sea. Lockne is a so-called concentric crater with a 7.5 km wide inner crater that is excavated in the crystalline basement, surrounded by a 3.5 km wide brim that forms the inner part of an outer crater formed in the upper, weaker and less dense part of the target (Lindström et al. 2005a). Despite the relatively high age, the Lockne crater is well preserved in comparison to many other even younger craters on land. It is due to that after the impact the crater was covered by the continued sedimentation and later by nappes of the Caledonian orogen (Ormö et al. 2013). The continuous sedimentation before and after the impact is marine, which shows that the impact occurred at sea. A substantial part of the crater infill as well as deposits in its close vicinity are sediments formed when the water rushed back into the newly formed crater, i.e. the "resurge". These deposits have the same bulk composition from bottom to the top and show a generally fining upward succession into sand and silt at the top.

At the Lockne crater the resurge deposits are separated into two parts; the lower coarse clastic Lockne Breccia and the arenitic silty sandstone named Loftarstone. According to von Dalwigk and Ormö (2001) the Lockne Breccia most commonly shows a gradual transition into the Loftarstone although it may occasionally exhibit a sharp contact (figure 2). Therriault and Lindström (1995) document materials with shock features such as frequent quartz grains with PDFs and impact melt fragments in the Loftarstone.

Figure 2. Loftarstone overlying the Lockne Breccia. **(**Left) Lockne Breccia expresses a gradual transition into the overlying loftarstone. Victorinox pocket knife as scale. Photography: E. Sturkell. (Right) Loftarstone resting with sharp contact on the Lockne Breccia. Same pocket knife as scale. The two localities occur 1km southwest of village Hällnäset and here 10 meter apart. Village Hällnäset is located circa three km from the center of the Lockne impact crater. (Lindström et al. (2005a). Photography: E. Sturkell.

4. An impact origin of the Vakkejokk Breccia

In the review article "The Lower Cambrian of Scandinavia: Depositional environment, sequence stratigraphy and palaeogeography" Nielsen & Schovsbo (2011) argue that the previous explanations about the origin of the Vakkejokk Breccia unit are unsatisfactory. Instead they infer that the coarse Vakkejokk Breccia has a meteorite impact related origin. They mention such features as the local disturbance of the underlying strata; the erosive character of the unit; the varied character of the breccia; that the breccia locally rests on the basement; the by Kulling (1964) reported large clasts; the fractured state of some of the basement derived boulders; that the breccia has an upwards grading into angular granitic gravel; the lateral variation of strata; and that the breccia is a local anomaly that cannot be traced in the successions along the eastern margin of the mountain chain.

The notion expressed by Nielsen & Schovsbo (2011) spurred a reinvestigation of the Vakkejokk Breccia by Nielsen and impact crater specialists Ormö and Alwmark. In the article "The Vakkejokk Breccia: An Early Cambrian proximal impact ejecta layer in the North-Swedish Caledonides" by Ormö et al. (2017) they present results obtained during three field expeditions to the Vakkejokk Breccia. They report that the conspicuous breccia is up to 27 meter thick, and they propose that it could be an ejecta layer from a hypervelocity impact at the epicontinental sea which surrounded Baltica during Early Cambrian. Based on strathigraphic arguments they date the impact to ≈520 Ma. In the western part (Vakkejokk/Orddajohka) the layer is five meter thick and in the eastern part (Tjäurajokk) the layer is 2.6 meter thick. Ormö et al. (2014, 2016, 2017) have identified 4 subunits; at top up to 30 cm thick arenitic sandstone which they named Top Sandstone, below this is a normally Graded Polymict Breccia, which is c. 1-3 meter thick and is dominated by crystalline clasts although relatively large siltstone clast sometimes occur in the upper part of the breccia. The Graded Polymict Breccia is relatively resistant to erosion and often crop out as a ledge. The Graded Polymict Breccia occurs as clast-supported as well as matrix-supported, and with clasts often transected by fractures. Below the Graded Polymict Breccia is a basal Lower Polymict Breccia that can be up to about twenty meter thick and containing mega-clasts inferred as ballistic ejecta from time of impact. Sporadically, either overlying or replacing the Top Sandstone, is a < 30 cm thick conglomerate, named Top Conglomerate. The Graded Polymict Breccia and the Top Sandstone are thought to have formed as marine resurge carrying ejecta and rip-up material towards the crater. Ormö et al. (2017) also write that the Top Conglomerate could be debris flow slumps from a degrading crater rim that protruded above the sea surface. Ormö et al. (2017) write that the largest clast they have measured have dimensions of 54 x 35 meter, thus concluding that the mega clasts reported by Kulling (1964) of a couple of hundred meters long most likely are several clasts sticking up in the forest that have been counted as one clast. Studies from samples from the Vakkejokk Breccia sub-units; Alwmark et al. (2016) and Ormö et al. (2017) report that the Top Sandstone and the Graded Polymict Breccia display planar deformation features (PDFs) in quartz grains. Through calculations of ejecta thickness, clast dimensions, and comparison with the Lockne impact-crater in central Sweden Ormö et al. (2017) propose that the suspected crater could be circa 2-3 km in diameter, but can be slightly larger. Ormö et al. (2017) suggest that the crater is most likely located below Vaivvancohkka, with a less likely alternative location in Torneträsk (figure 3). Their hypothesis is that a cosmic impact occurred in an epicontinental sea that had a water depth of circa 25 meter.

5. Method

In august 2016 the author together with J. Ormö started the core drilling project with a four day fieldwork at a Vakkejokk Breccia locality about four kilometers south-east from Orddajohka (figure 3). The workplace was located about 260 meters above the surface of Torneträsk. It was important to find a diamond core drilling equipment that was portable and capable to drill out a core with a diameter of 45 mm to a depth of at least one meter. The choice was the HILTI DD-200 stand-mounted diamond core driller. We succeeded to obtain three vertical core samples named Vakk-CH1, Vakk-CH2A and Vakk-CH2B. In connection with the core-drilling, bedrock exposures close to the drill site were examined and described; such as the different sub-units of the Vakkejokk Breccia, Red and Green Siltstone Member, which overlay Vakkejokk Breccia, the underlying Lower Siltstone Member, and the Lower Sandstone Member, which rest on the crystalline Proterozoic basement. The outcrops are known from the fieldwork carried out by Ormö and Nielsen during their mapping campaigns (Ormö et al. 2017).

The HILTI DD-200 has an effect of 2.6 kW. During drilling the corer was mounted on a drill stand of the model DD-HD 30, which was bolted to the rock outcrop. The power supply to the corer was provided by two parallel connected, gasoline powered portable Honda EU 20i AC generators with a combined effect of 4 kW. The chosen diamond core bit of the brand HILTI with an outer diameter of 52 mm and a working length of 45 cm. This together resulted in of 42-45 mm diameter drillcores. The positioning of the drillholes was done with a handheld Garmin MAP60C GPS. Positioning of the corer was done at an exposed transition from Top Sandstone to the underlying Graded Polymict Breccia.

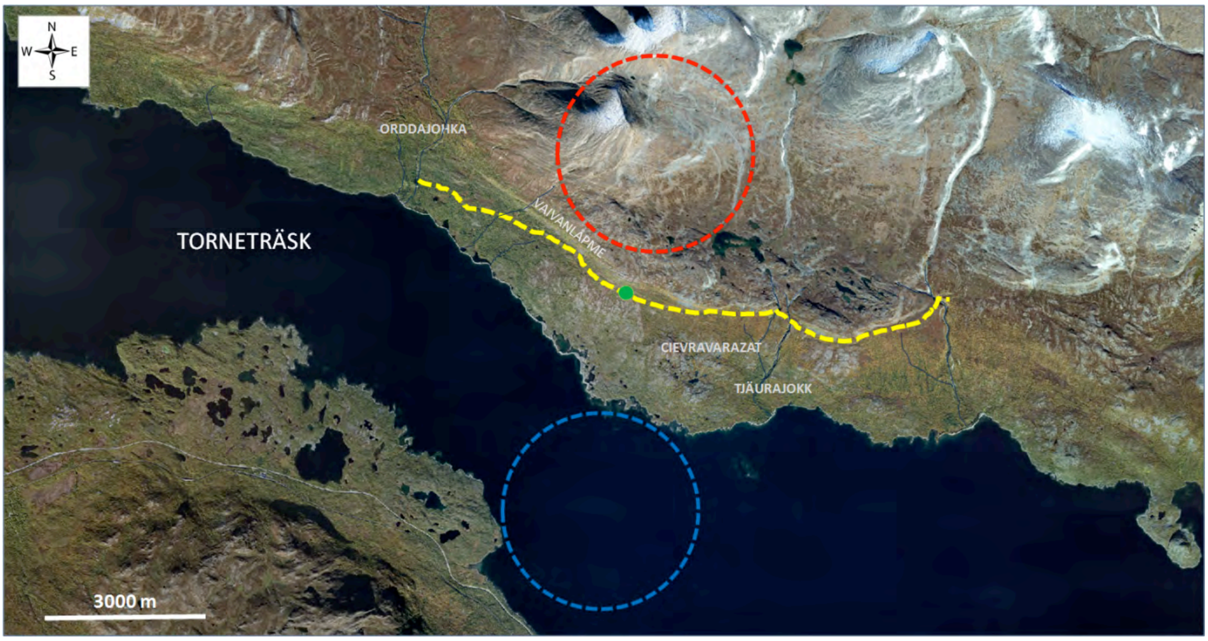

Figure 3. The two putative impact crater locations with the most likely indicated by a red dotted circle, the less likely location of a crater is indicated as a blue dotted circle (modified from Ormö et al. 2014, 2017). The yellow dotted line indicates the Vakkejokk Breccia layer (modified from Kulling 1964 figure 7; Ormö et al. 2017 figure 2). The green point indicates the fieldwork area and drill site. The figure is modified from National Land Survey of Sweden, accessed Mars 2017.

The core drilling was carried out at three positions within a 50x100m wide field of outcrops in the relatively more proximal part of the ejecta layer as defined by Ormö et al. (2017). The three drillcores are displayed in figures 7, 10 and 12.

Each core was cut longitudinally into two halves. Cutting was done with a table mounted diamond cutting saw manufactured by Diamant Boart TS350 S. One half of each core was then grinded and polished. Polishing of the samples was done on a Struers RotoPol-35 with polish grit as fine as P1200.

Subsequently the polished core half was photographed with a Nikon D3200 digital camera in the highest resolution mode. The photos were loaded to the image analyze software JMicroVision v1.2.7 by N. Roduit which is a software designed for measuring and quantifying components in high-definition images. The lithological study was performed with up to circa 2 fold magnification with loupe and software JmicroVision.

In the software a 2D-boundary-box (further in text "2D-box") with height x length -> 4 x 5 cm = 20 cm^2 was shaped, the 2D-box was moved five cm (step by step) along the core in the photo. All of the clasts in the 2D-box over the chosen cut-off size ≥5 mm (longest clast dimension, see Ormö et al. (2007) were manually outlined, which allowed the software to line up the total number of clasts in the 2D-box as well as each clast length, area and eccentricity of those visible inside the perimeter of the 2D-box. In the case that the clast protruded outside the 2D-box only the length axis of its visible part within the 2D-box was measured i.e., those parts outside of the 2D-box were considered as unknown. Then the total clast area could be calculated by subtracting the total clast area from the 2D-box area (20 cm^2) which resulted in percentage of matrix. The mean clast size, number (amount) of clasts in the 2D-box and proportions between different clast lithologies such as granite and siltstone clasts were

calculated in the software Microsoft Excel. Lithology determination of clasts was done manually.
The size sorting was calculated as the standard deviation of the mean clast size for each 2D-box following the methodology by Ormö et al. (2007). Notwithstanding the attempt to receive equal as possible spacing between the data points along the core, some of the core pieces were already broken resulting in that the 20 cm^2 2D-box mismatched here and there giving somewhat uneven data point spacing in the graphs. The preparation of the each clasts analyzed data (a row in software JMicroVision V1.2.7) was done in the software Microsoft Excel.
The data where plotted as graphs, such that data for each drillcores is shown in six graphs. Every graph has the positive y-axis downwards against depth (in cm) of the drillcore. The x-axis correspond to data collected from each 2D-box (as a point) such as Matrix in %, Mean clast area in cm^2, Mean clast sphericity i.e. eccentricity (grain length/ grain width), Size sorting, Amount of clasts, Crystalline clast in % of total. The sum of each al clast lithologies is seen at end of section 6.5. The clasts were subjectively determined/classified and manually added; clast-lithology by clast-lithology into Microsoft Excel sheet. From the presentation and calculation of clast sizes and the size sorting follows Ormö et al. (2017, p. 1931) albeit adapted from the original line-logging technique to be applicable to the box-logging technique used here: Phi values where used when analyzing the clast size distribution. The definition for the phi value is $\Phi = -\log_2 d$, where d is the grain diameter in millimeters (Krumbein 1934 as cited in Ormö et al. 2007, p. 1933). The phi values are then converted to positive phi values (i.e., $-1*\Phi$) for convenience in the calculations. A brief description of each observed clast lithology is also given.

6. Results

6.1. Geology at drill site

In the close vicinity of drillsite the four sub-units of the Vakkejokk Breccia (see Ormö et al. 2017) as well as the lower three members of the Torneträsk Formation are exposed and the basement (see chapter). The drillsite itself is located about 260 m above the surface of Torneträsk. The exposed sequence is described from higher to lower stratigraphic position:

The Red and Green Siltstone Member outcrop as a few meter high terrace displaying parts of the greenish siltstone in a position overlaying the Vakkejokk Breccia somewhat to the north of corehole Vakk_CH1 (figure 5A). On sligthly the same altitude, just below the Red and Green Siltstone Member some 20 meter east of the borehole Vakk_CH1 there is an outcrop of the the Top Conglomerate unit. Here it is silty, matrix supported, and is dominated by rounded to sub-rounded crystalline clasts (figure 5B). One of the clasts could bee a sandstone. Figure 15C shows the Top Sandstone unit at the location of borehole Vakk_CH1 where it is seen as a 1-3 decimeter high ledge. This locality is in a stratigraphic position just below the Top Conglomerate unit. Figure 5D and figure 5E are from the location of Vakk_CH2A, which is located about 70 m to the west of Vakk_CH1. It shows the topmost part of the Graded Polymict Breccia unit with contorted dark siltstone and equidimensional granite clasts, mostly of centimer size or smaller, but occasionallt some about 2-7 cm. All clasts are swimming in a light greyish, sandy matrix (GSA photo-scale as refernce). The circled green siltstone clast is about 5 x 2 dm long (figure 5D). It is just at the transition to the Top Sandstone, so it can also be seen as a bimodally sorted part of the Top Sandstone. Possibly, the siltstone fragments were more easily transported than equal size crystalline clasts occurring in the underlying Lower Polymict Breccia unit. Figure 5F shows the clast-supported Graded Polymict Breccia unit at an outcrop some tens of meter south of Vakk_CH2A. Here it has a brown-orange colored matrix containing light-gray, angular granite clasts and greenish siltstone clasts (mostly seen transfomed into semi-matrix). To the south of the drillsite the Lower Polymict Breccia unit outcrop in a terreace (5G-1), geographically and stratigraphically just below the Graded Polymict Breccia and Top Sandstone of the outcrops that were cored. At the base of the terrace a mega clast stand out. The Lower Polymict Breccia unit is followed downwards by more intact Lower Sandstone Member (figure 5H) including sandstone with ripple marks. Outcropping basement at the bottom of the profile shows red gneiss (figure 5I). Some hundreds o meters south-east of the drill site in a small mire stream is an *in situ* matrix-supported bottom conglomerate, which contains rounded quartz-pebbles in a dark sandy matrix (figure 5J-1). About three meters further downstream the matrix of the bottom conglomerate changes to a slightly lighter colored sand, and the clasts become sub-rounded (figure 5J-2). The bottom conglomerate is stratigraphically located between the Lower Sandstone Member and the Proterozoic basement (Thelander 1982). Further about 200 meter south of the mire stream is the area of the hump Cievravarrazat where the Proterozoic crystalline basement shows signs of glacial erosion (figure 5K) . The granite of the basement has a red color, and the terrain west of Cievravarrazat is low wegetated, the depressions are mostly covered by Quaternary deposits and small vegetation.

Figure 5. Geology at drillsite. (A) Cliff of green siltstone of the Red and Green Siltstone Member "RGSM", which overlain the Vakkejokk Breccia "VB". (B) Top Conglomerate Dotted circle indicates potential sandstone clast (C) Top Sandstone as a small ledge; Location of borehole Vakk_CH1. (D) Graded Polymict Breccia (GPB) with silt clasts in a grayish matrix. (E) Close-up view of previous figure. (F) Close-up view of (GPB). (G-1) Terrace where Lower Polymict Breccia (LPB) seems intercalated in the Lower Sandstone Member (LSM), here containing a mega clast. (G-2) Close-up view of the mega clast. (H) Outcrop of sandstone belonging to the Lower Sandstone Member. (I) An exposure of a light red gneiss of the basement. (J-1) Bottom conglomerate containing vein-quartz clasts in a dark sandy matrix. (J-1) About three meters downstream, clasts in a light sandy matrix. (K) Proterozoic basement at Cievravarazat (encircled hammer for scale). Photography: P. Minde 2016.

6.2. Drillcore: Vakk_CH1

The coring resulted in a 135 cm long drillcore with 0.7% core loss (figure 7). The position of the borehole was N68˚ 22.259’, E19˚ 14.132’. The logging results are presented in the graphs in (figure 6). The clast parameters are changing and variations are displayed in graphs (figure 6). A composite photo of the whole drillcore is visible in figure 7. The description starts from the uppermost part of the drillcore. At top of the core is sandstone, which belongs to the Top Sandstone unit. Until circa 40 cm depth the sandstone shows normal grading. In the uppermost 20 cm there is repeated bedding with each bed circa 1-3 cm in thickness. At a depth of 23-25 cm the sandstone expresses transition into slightly coarser normally graded sandstone without repeated beddings, and possibly an erosive contact between sandstone and a siltstone (figure 7). The sandstone contains some sporadic circa 5-10 mm long granite clast at a depth of 30-39 cm. At the depth of circa 39-42 cm the sandstone expresses a transition into a clast-supported breccia with greenish matrix, which contains light gray granite clasts. At 44 cm an almost round greenish siltstone clast is seen. Figure 8: at a depth of 58 cm there is a 4.1 cm long particle classified as a "fine grained black green clast/particle with white specks" (figure 7); it is classified as melt (?). At a depth of 60-78 cm the greenish clast-supported breccia expresses a transition to a polymict matrix-supported breccia, with a dark reddish matrix. Clasts are mostly of brown, angular granite; at the transition the granite clast seems to have adapted the color of the matrix. At a depth of 70 cm green matrix hosting light grey clasts changes to dark-red- brown matrix with greenish flames hosting brown granite clasts and a rounded, red chert clast. (*text continues on page 15*).

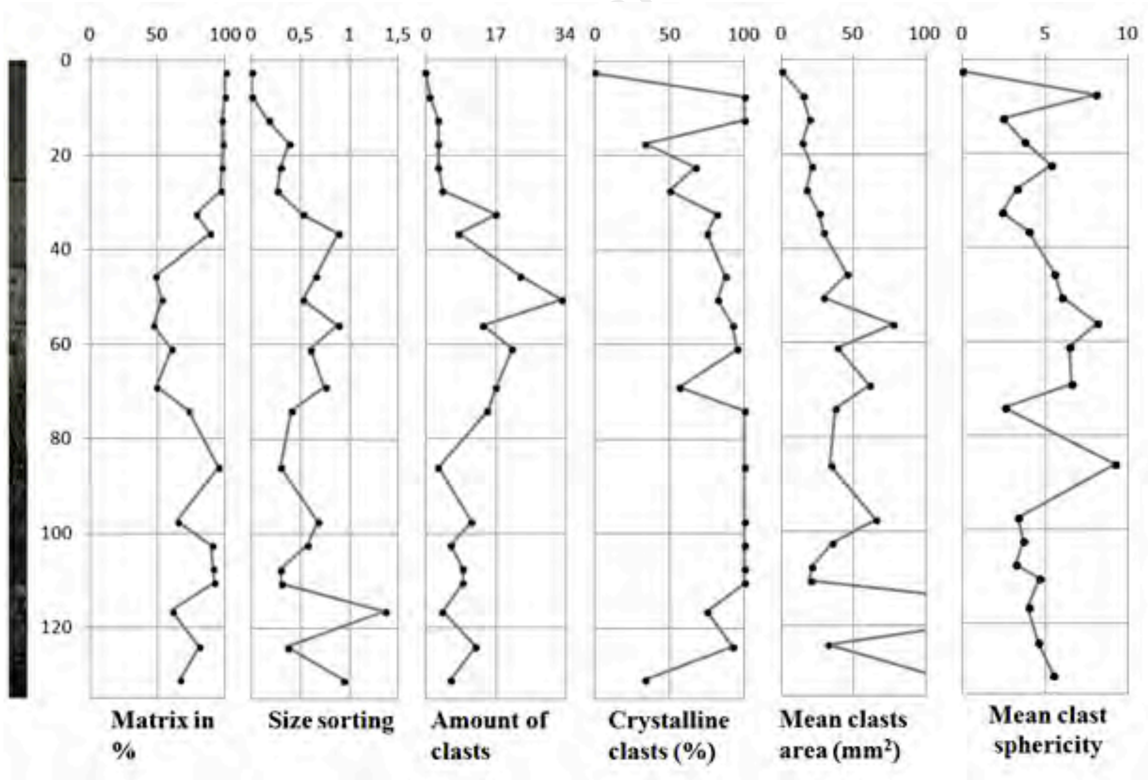

Figure 6. Drillcore-Vakk_CH1: Six graphs that show the variation of clast-parameters. To the left is a miniature image of the whole drillcore. The clast data are generated by JMicroVision and show the variations of parameters of the analyzed drillcore clast and matrix. The scale of y-axis is in cm, each black point representing the center position of the logged 2D-box (see method chapter).

(Continued text from page 14): From 78-135 cm the breccia is matrix supported with a dark red matrix with distinct green colored flames (interpreted as disintegrated green mud/siltstone). At the bottom part of the drillcore (120-135 cm) are dark red siltstone clasts and sub-angular granite clasts all in a dark brown matrix. The breccia shows a normal grading, but mostly in the uppermost part until circa 40 cm depth. The crystalline clasts dominate. Mean clast area increase upwards. The mean sphericity has no direct trend along i.e. same al the drillcore. Above 30 cm the matrix ratio is almost 100% and amount of clast is circa 0%.

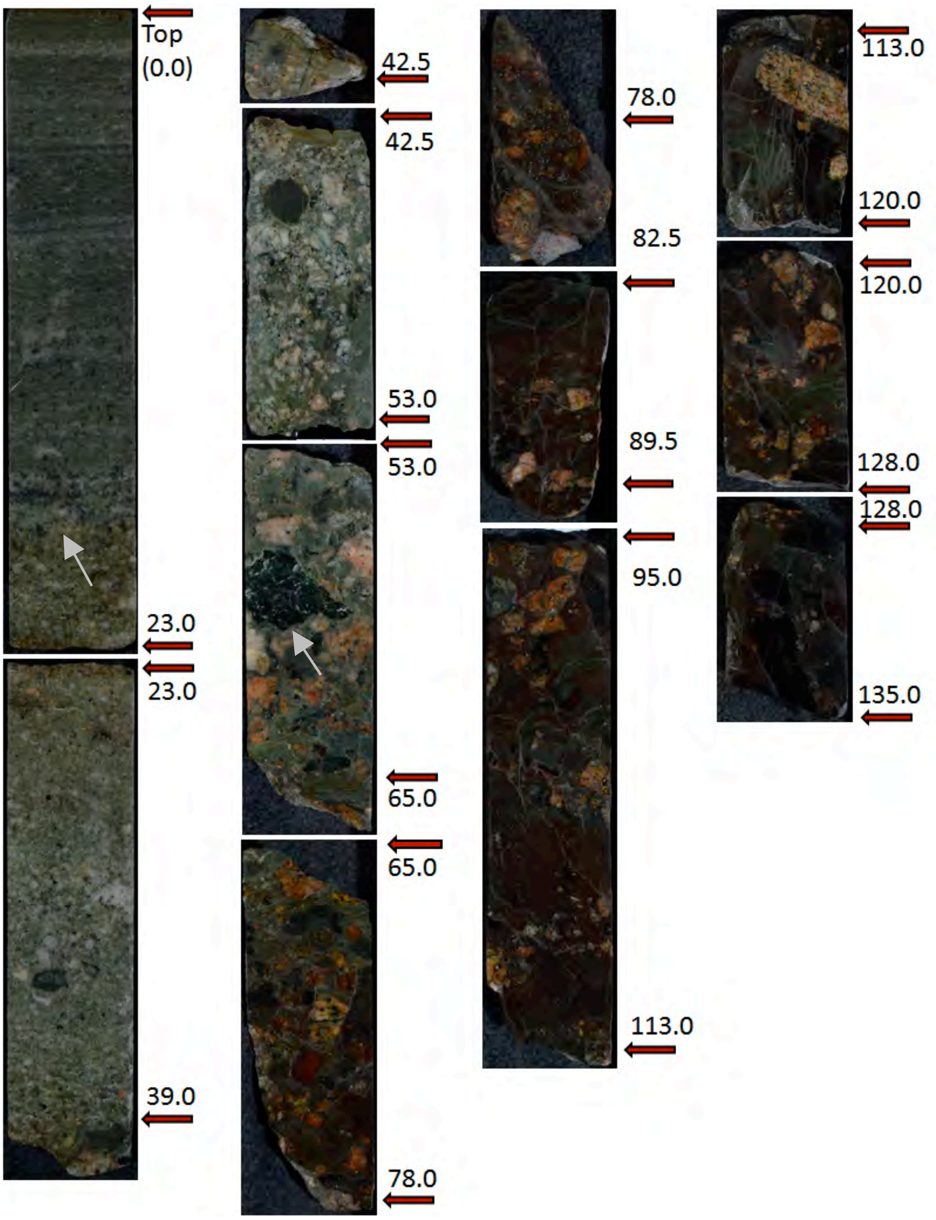

Figure 7. Drillcore (Vakk_CH1): This drillcore consists of ten (10) core pieces. The top-most part of core starts from upper left in figure. The depths are indicated by red arrows (scale is in cm). The white arrow at 20 cm depth points out a contact between fine sandstone to coarse sandstone. The white arrow at 60 cm points out a "fine grained black green clast/particle with white specks" (see text). Repeated bedding between 0 to 20 cm.

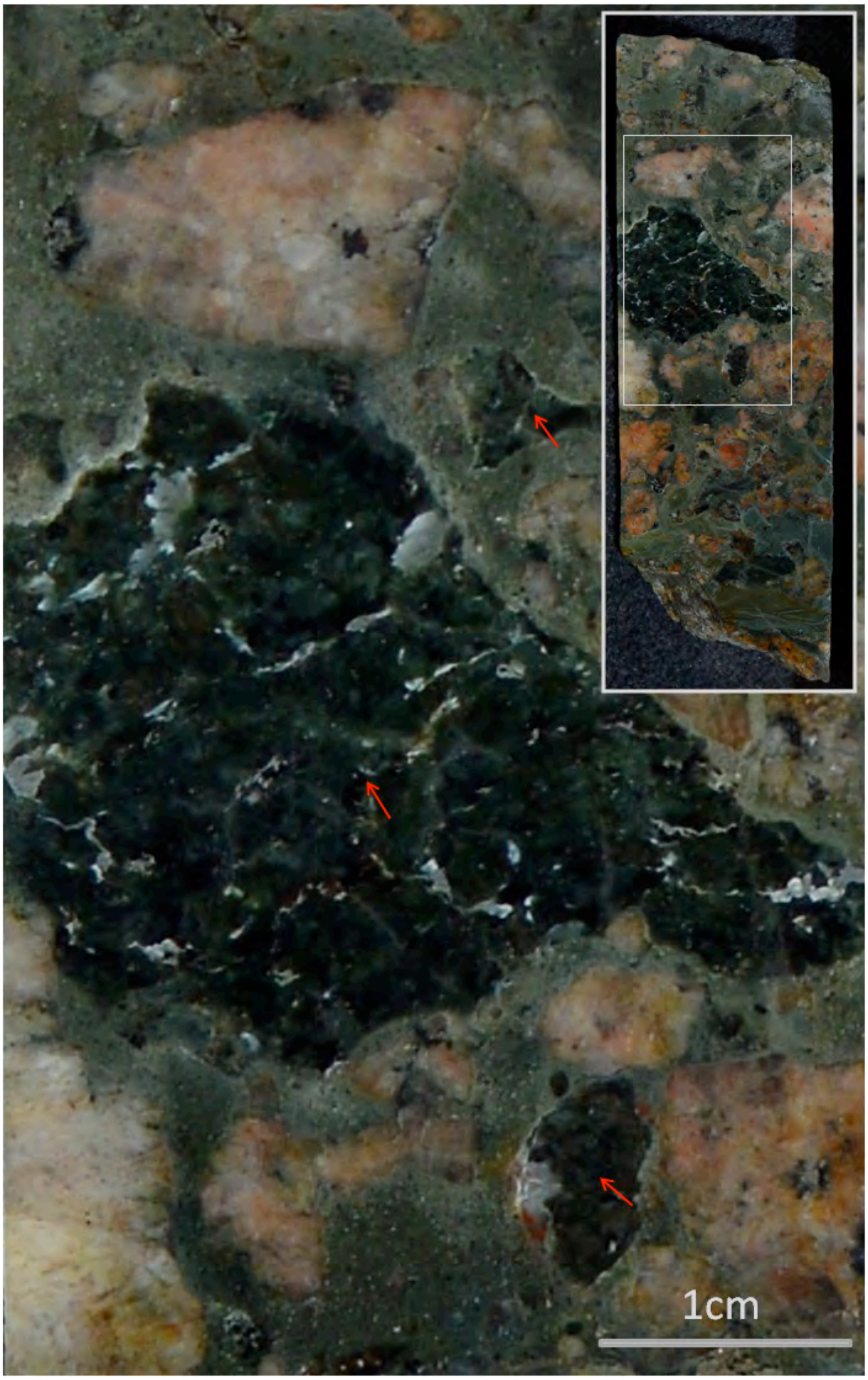

Figure 8. Close-up-view of a clast in drillcore Vakk_CH1 (at c. 60 cm depth). It shows a fine grained, black-green lithology with white specks. There are also two smaller clasts of the same type as the big one. The clasts are angular- too sub-angular. The black clasts are categorized as possible melts. To determine the clast lithology it has to be studied by optical analysis in thin-section or geochemistry. The inset shows the whole core piece with the main image location indicated.

6.3. Drillcore: Vakk_CH2A

This drilling resulted in an 85 cm long drillcore with 1.2% core loss. The position of the borehole was N68˚ 22.269', E19˚ 14.013'. The logging results are presented in the graphs in Figure 9. A composite photo of the whole drillcore is visible in Figure 10. Description starts from the uppermost part of the drillcore and continues downwards. At the top of the core is a conspicuous blackish clast, which covers the whole core surface. It is classified to category "black/green fine grained with white specks" (figure 9). This black clast was visible at the outcrop and influenced the decision to drill the core at this spot. At outcrop surface the clast formed a shallow weathering pit, the country rock seemingly being more resistant to erosion.

Some of the silt-clasts below the blackish clast are obvious disintegrated into the matrix. The crystalline clast content drops at 20-30 cm depth. The mean clast eccentricity is varying between ~2.5 and 6 and the siltstone clasts have generally a higher value of eccentricity than the granite clasts. The sorting is good at top, but decreases downwards. Two large clasts seen at the top of Figure 9 affect the generated graphs. Nevertheless, it is an indication that flattened siltstone clasts occur in the sandstone here and there, which also is seen in outcrop (fig. 5D). Intervals of coarser sandstone occur sporadically down to circa 45 cm. Just below 36.5 cm depth is a sharp, inclined contact (circa 50°). At 38 cm is a black clasts and at 57 cm another, these are possibly phosporites. Downwards, the coarse sandstone is interchanging with breccia with some centimeter long green-gray siltstone clasts, giving an impression of repeated bedding. From 47-85 the breccia becomes dominantly clast-supported, containing light gray granite and green siltstone clasts.

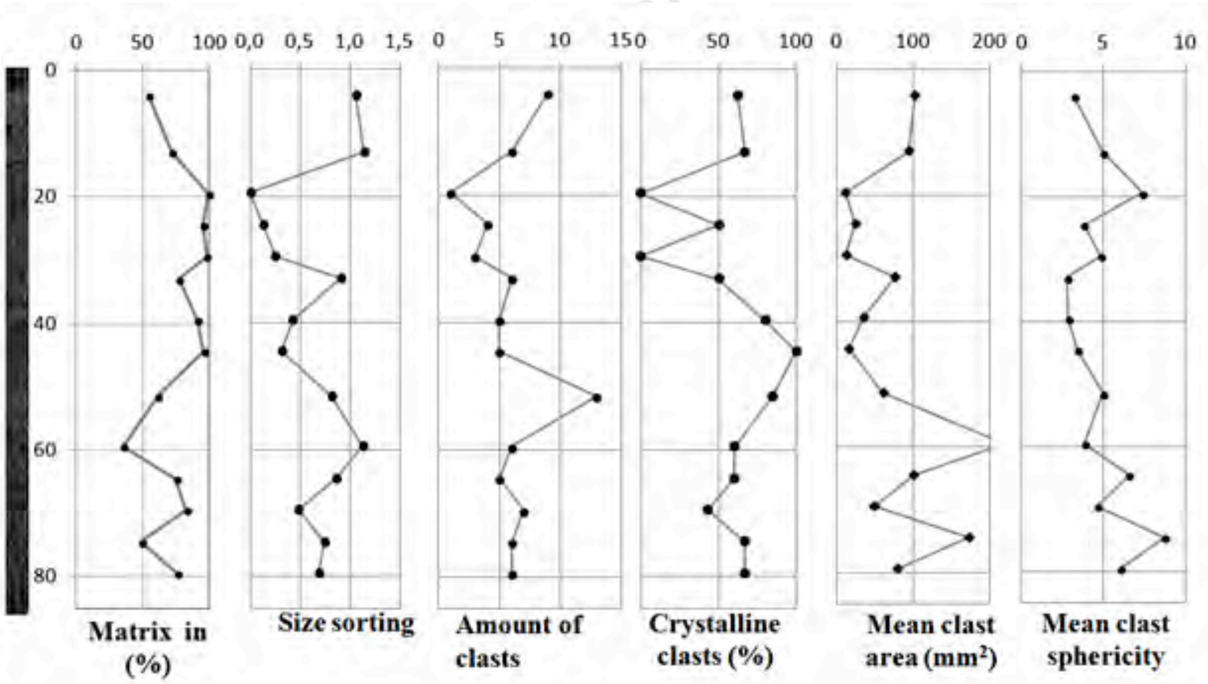

Figure 9. Drillcore-Vakk_CH2A: Graphs showing the variation of clast-parameters. To the left is a miniature image of the whole drillcore. The scale of y-axis is in cm, each black point representing centrums of a 2D-box.

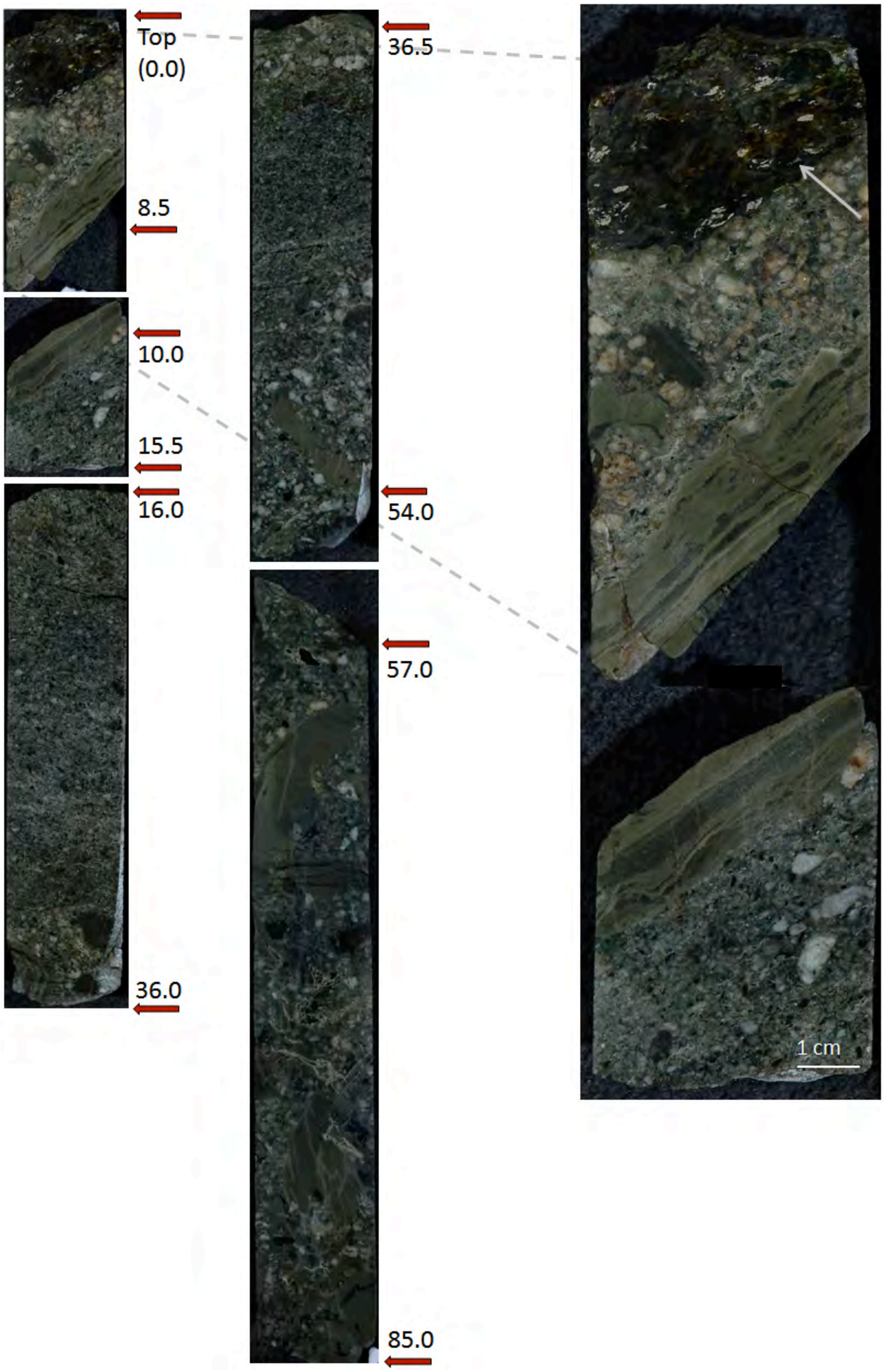

Figure 10. Drillcore Vakk_CH2A. The top-most part of drillcore start from upper left. The depths are indicated by red arrows (scale is in cm). To the right is a close-up view of the Black-green, fine grained particle with white specks (gray arrow), which is a possible melt clast.

6.4. Drillcore: Vakk_CH2B

This drilling resulted in a 135 cm long core, with no core losses. The position of the borehole was about one meter to the north of borehole Vakk_CH2A. The logging results are shown in graphs (Fig. 11). A composite photo of the drillcore is given in figure 12. Description starts from the uppermost part of the drillcore. From 0 to 30 cm the drillcore consists of sandstone with a pocket of coarser sandstone between 12 and 21 cm. Below 30 cm there is a coarse sandstone with mainly green-grayish silt clasts as well as some circa 5 mm long, light gray granite clasts. At a depth of 85 cm is a pyrite swarm with a dimension circa 2-4 cm^2. The gray matrix change to gray-blackish below circa 70 cm. Between 75 and 98 cm the crystalline clasts are frequently intersected by thin fractures and some of these clasts display a yellowish tint. From circa 75 cm the breccia containing light colored crystalline clasts and the matrix is blackish-brown until circa 116 cm where a fragment (2-3 cm) of dark green-blackish siltstone with black streaks appears. Below this clast the matrix has a slightly lighter color, almost the same color as at 33-42 cm. The two closely positioned boreholes VakkCH_2 and VakkCH-2B both display a coarser clast size distribution than at the same position in the drillcore Vakk-CH1. No distinct variation of trends.

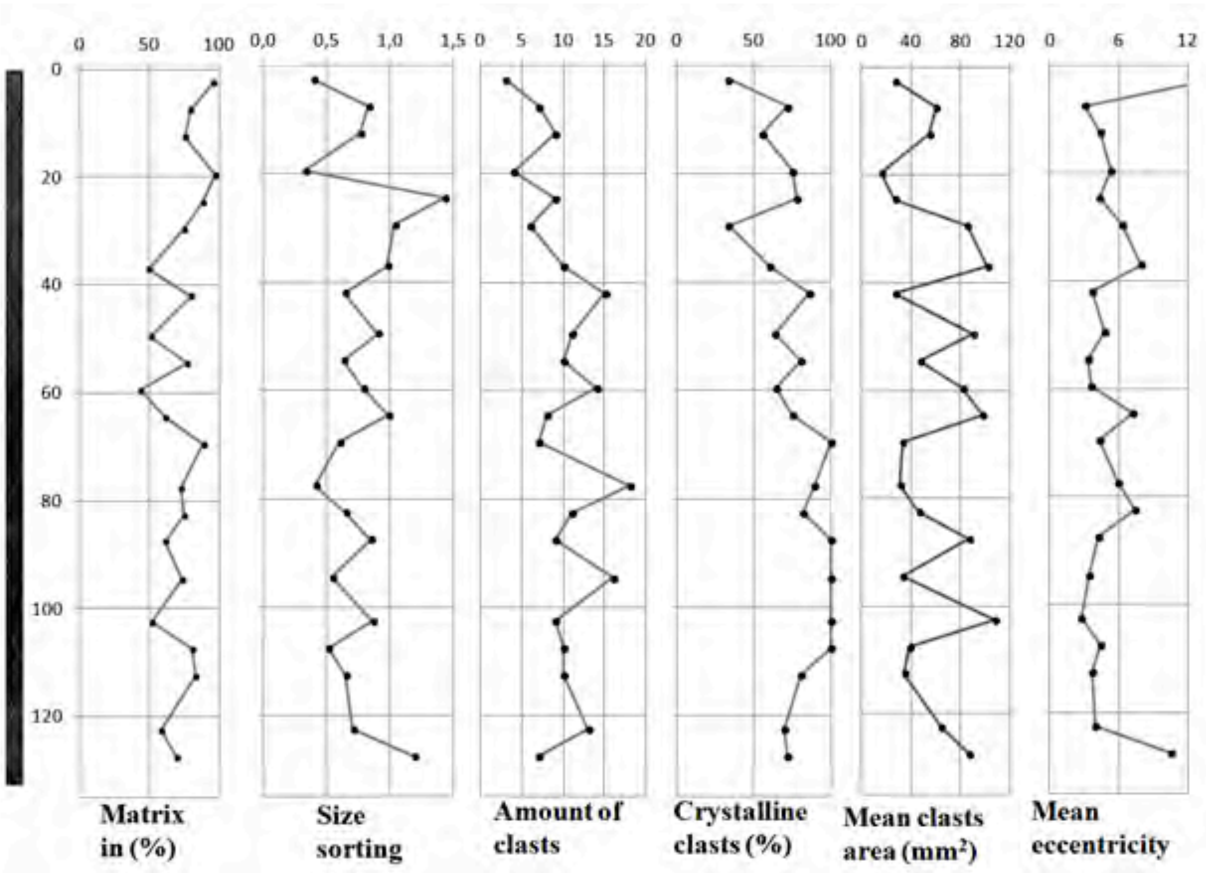

Figure 11. Drillcore-Vakk_CH2B: Graphs showing the variation of clast-parameters. To the left is a miniature image of the whole drillcore. The scale of y-axis is in cm, and black point represent center positions of the logging 2D-box.

Figure 12. Drillcore (Vakk_CH2B) consist of eight core pieces. The top is at upper left. The depths are indicated by red arrows.

6.5. Clast lithologies

In the three drillcores a total of 517 clasts ≥5 mm in length were measured. Of these 78.6% is interpreted as granitic, 21.3% siltstone, and 1% other lithologies. The clasts can be further separated into seven categories, of which the first four occur in abundance, whereas the last two can be considered as accessory. **Clast-type 1**: Light-gray, granitic clasts (figures 13A and 13B). A single brown crystalline clast occurring in the same matrix shows a slight yellowish tint (figures 13C). **Clast-type 2:** Brown granite clast, frequently occurring in a dark-reddish brown matrix (figures 13D). Close-up view, a part of a round rod shaped (prolate) brown granite clast (figure 13E). **Clast-type 3:** Figure 13F shows a green siltstones clast, the clast is surrounded by mainly light gray small < 5 mm granite clasts. In figure 13G is a sub-rounded dark brown-red siltstone clast in brown matrix. **Clast-type 4:** In figure 13H a rounded chert in a mainly brown, silty matrix with a few small brown granite fragments.

Clast-type 5: Figure 13I shows a black colored clast with reducted rim, possible a phosporite or a melt fragment in stishovite. **Clast-type: 6:** In (figure 13J) is a clast categorized as possible melts, the clast is black/green, fine-grained with specks. Here in a green matrix of the Graded Polymict Breccia.

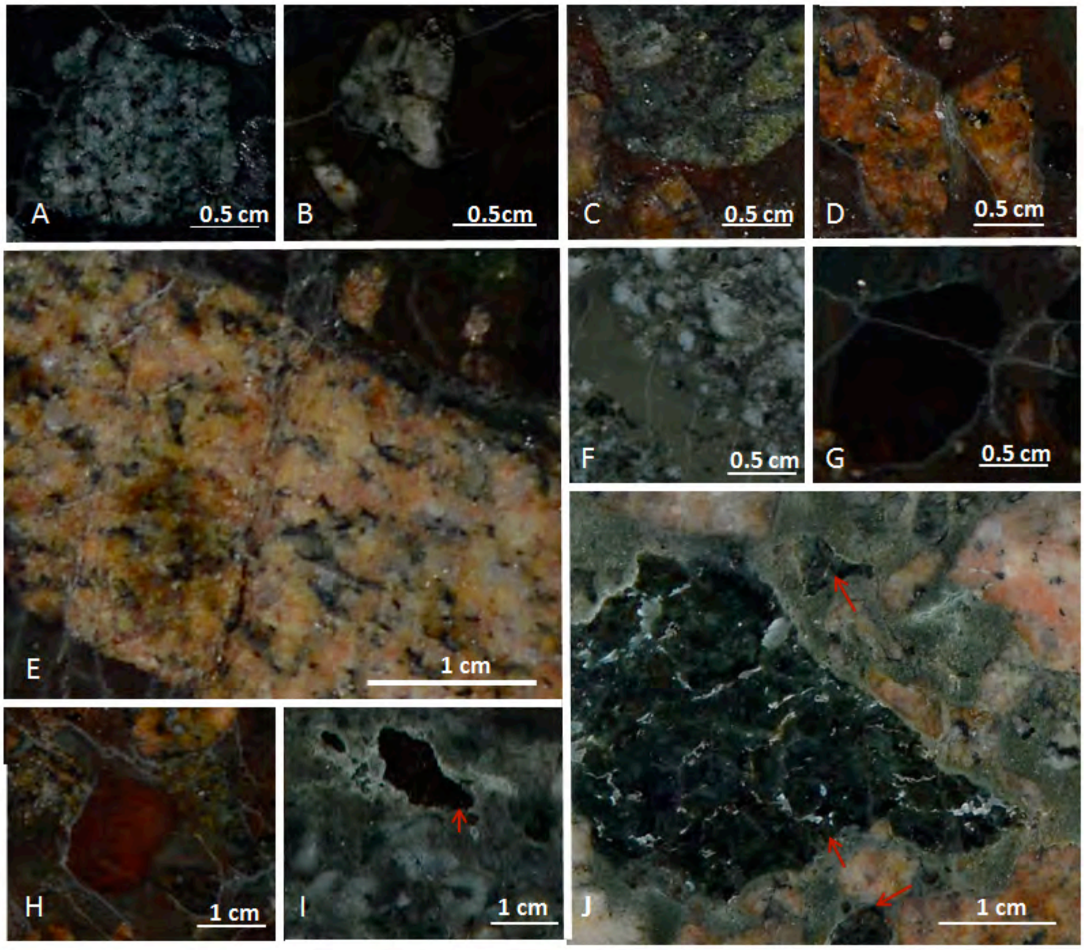

Figure 13. Clast lithologies. (A and B) Angular light-gray granite in a dark matrix. (C and D) Brown angular granite clast in a brown matrix. (E) Brown granite clast. (F) Green siltstone clast, here closely surrounded by light white granite clasts and granite granules. (G) Dark-brown siltstone clast in brown matrix. (H) Accessory: red chert; (I) black clast possible a phosporite or a melt fragment. (J) Black/green clast fine-grained with specks (also at fig.8).

At the upper part of the drillcore Vakk_CH1 (at 36 cm depth) are two small lithic fragments or single minerals that are "carrot-orange" colored, possible categorized as alkali feldspar or minute fragments of the brown-red granite, here together with mostly quartz grains in a coarse, to very coarse sand with a greenish cement-matrix, as well as one black colored grain (figure 14A). The location is within the lower part of the Top Sandstone, here in an obvious normal graded (fining up sequence). At a depth of 78 cm in drillcore Vakk_CH1 (figure 14B) is a brown crystalline clast which contains fractures, surrounded by a brown red matrix.

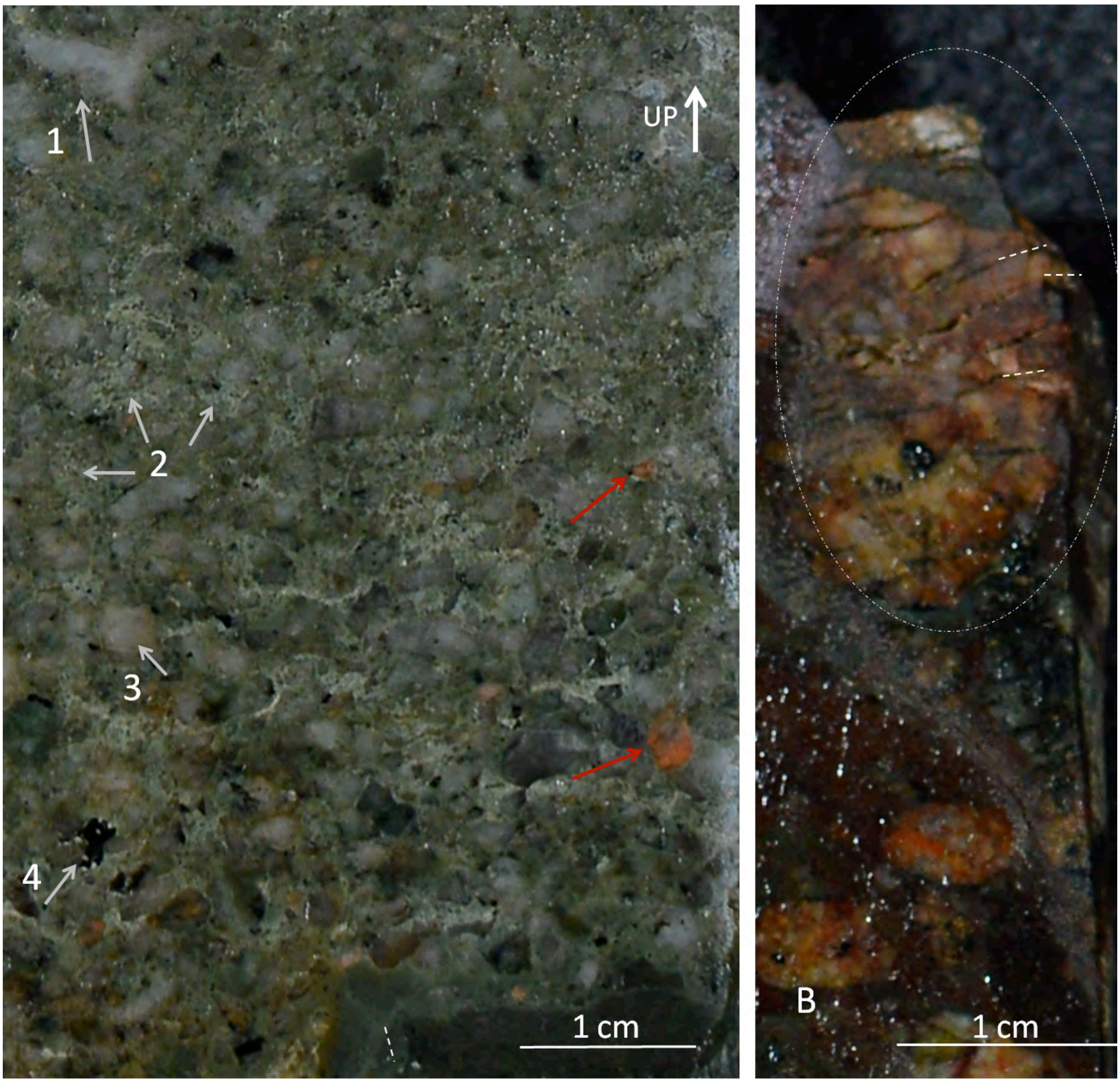

Figure 14. Sandstone. Brown and clast. (A) Drillcore Vakk_CH1: Within the greenish, coarse Top Sandstone at Vakk_CH1 at a depth circa 38 cm, there are two small orange – carrot- colored grains (red arrows). Possibly small fragments of brown-red granite or monomineralic alkali feldspar grains. Arrow-1 and arrow-3 point out round grains possible quartz. The grain is surrounded by greenish cement, or matrix (arrows-2); Arrow-4 point out a black fragment. (B) Red-brown granite clast (encircled) showing thin fractures (dotted line at clast indicate fractures). The matrix is brown and the fractured clast is surrounded by brown smaller red brown granite clasts. Photo: J. Ormö 2016.

Summary of drillcore VAKK_CH1. Of a total of 220 logged clasts 182 are granite clasts and represents 83.1 %. The 34 siltstone clasts represent 15.6 % and the accessory two clast lithologies represent 1.3 %. Of the granitic clasts the light-gray variety represents 54.4 % and the rest is brown granite. Of the siltstone clasts 67.6 % are of the variety dark-green siltstones and the rest of the dark brown-red variety. The siltstone clast has generally a lower sphericity than the crystalline. The siltstone and granite clasts are mostly angular.

Summary of drillcore VAKK_CH2. Of the 82 logged clasts 51 are granitic and represent 63.7 %. The 29 siltstone clasts represent 36.3 %. The accessory two clast lithologies represent 2.4 %. Of the granitic clasts 100 % are categorized as light-gray. Of the siltstone clasts 79.3 % are dark-green siltstones, the rest is of the dark brown-red variety. The siltstone clasts are angular and generally of low spherocity to elongated, some is highly elongated (best seen in outcrop). The crystalline clasts are mostly angular with a low to moderate sphericity. Some of the siltstone clast seem oriented along bedding.

Summary of drillcore VAKK_CH2B. Of 215 logged clasts granitic clasts represent 78.6 %. Of the granitic clasts light-gray represents 95 %, the rest is of the brown variety. The latter are all confined to the same core segment at a depth of 69.5 to ~80 cm. The 109 siltstone clasts represent 21.4 %. Notably, no other clast lithologies occur among those logged. The siltstone clasts are angular and generally of low sphericity to elongated, some are highly elongated (best seen in outcrop). The crystalline clasts are mostly angular with a low to moderate spherocity.

6.6. Geological features and matrix

At drillcore Vakk–CH2A at a depth of 57 cm there is a black 3.5 mm long clast (figure 15A), which shows a slightly bluish white rim. Figure 15B demonstrates a dark crystalline clast, which has pyrite crystals interlocked with the other minerals. Pyrite is found both in the matrix, in siltstone clasts, and occasionally in a crystalline clast. Swarms of micro pyrites (<1 mm) are found here and there in the darker matrix. A swarm of cubic pyrite crystals is seen in a green siltstone clast, under the loupe they seem euhedral to subhedral. Figure 15C shows a pyrite swarm formed as a "hook-like/teardrop pod-form" in a green siltstone clast. At mesoscopic scale some of the light gray granite clasts are frequently intersected by thin fractures in several directions (figure 15D), however also brown granite clasts show fractures (figure 14E). Arrow-2 in figure 15D shows that a granite clast close to a pyrite swarm has a tint of yellow. Figure 15E arrow-1 point out a suspected round clast (possibly a vein quartz), and a brass yellow crystal classified as a chalcopyrite, as well as a granite clast which exhibits parallel fractures. Figure 15F shows the drillcore Vakk_CH2A at a depth of 63-73 cm; here are three features that resemble nebulae, these could be weathered melts. Diverse sections exhibit different colors (figures 15G-15K); the matrix at drillcores comprises green, brown-red, green-brown, gray, almost black matrix, the red matrix variety is seen at outcrop at drill site (figure 5F).

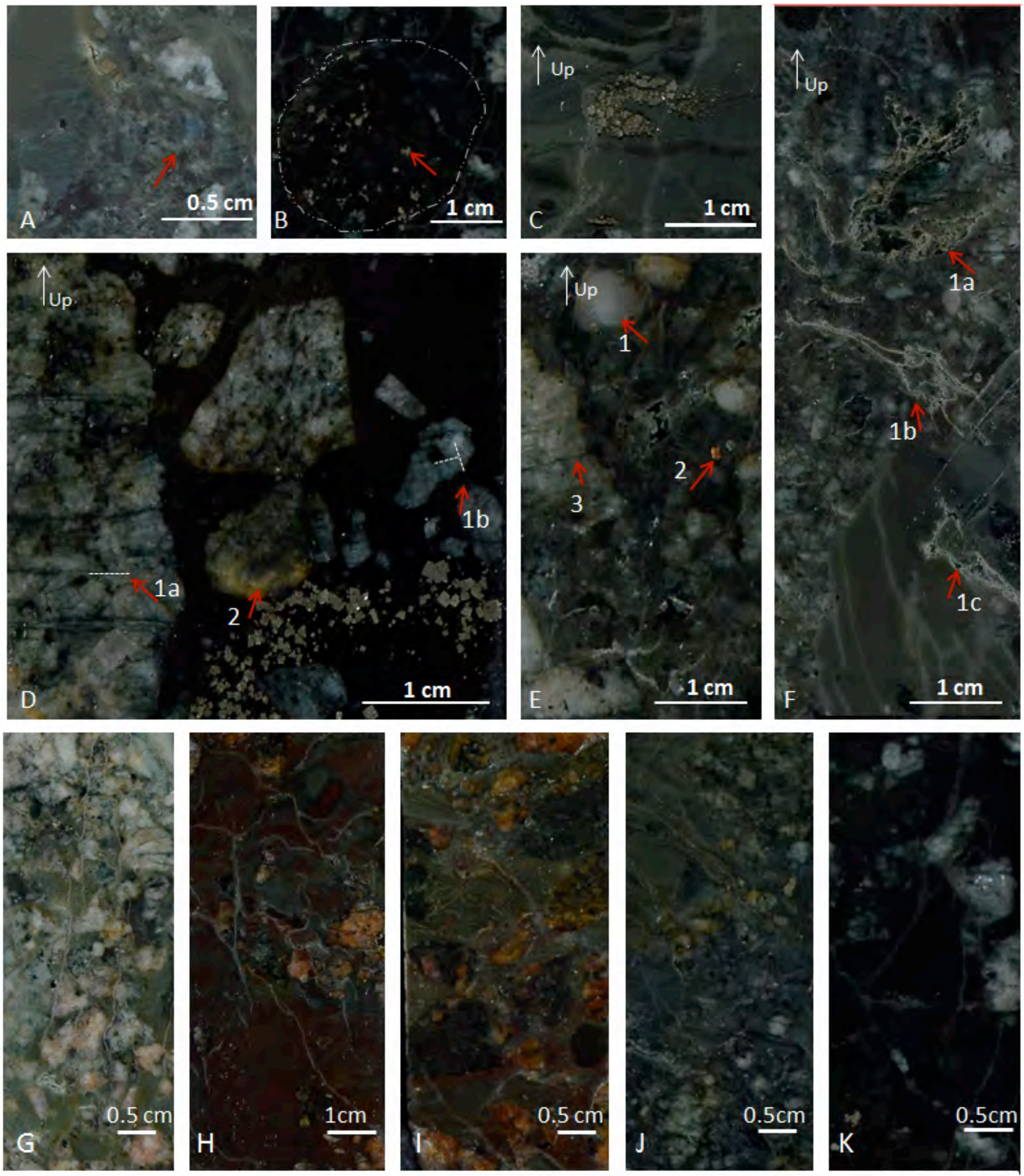

Figure 15. Clasts, features and matrix colors. (A) The arrow point out a granule which exhibits a blue pearly tint. (B) Dark crystalline clast (outlined by dotted line) here with pyrite crystals interlocked, the arrow point out a pyrite grain. (C) Granule pyrite swarm arranged like a teardrop or a hook-like pod with a tail of micro pyrites. (D) Light gray granite clast intersected by fractures in several directions (arrows 1a-b), arrow-3 point out a yellowish tinted clast, which has a swarm of pyrite crystals close by. (E) White clast, possible vein quartz (arrow-1); arrow-2 point out a crystal with metallic luster, brass yellow, possible a chalcopyrite grain, as well as granitic clasts intersected by fractures in several directions (arrow-3). (F) Arrows point at features that may be mineral precipitation in vug spaces, or possibly some remnant of chemically weathered melt. Close-up view of five diverse sections from the three drillcores: (G) green matrix. (H) Brown-red matrix with greenish flames. (I) Green brown matrix. (J) Gray matrix. (K) Almost black matrix. Photography: J. Ormö 2016.

7. Discussion

7.1. Putative crater rim

The approximate height of a crater rim from a newly formed two km wide crater on land is about 80 meters (Pike 1977 as cited in Ormö et al. 2017). The rim height, minus the water at the time of a putative hypervelocity impact should result in that the crater rim would have reached approximately 55 meter above the surrounding sea level. A rim of this height should stop the water rushing back towards the crater, unless there were some breaches in the rim.

7.2. Vakkejokk Breccia at drill site

The examination of the three drillcores retrieved from the Top Sandstone and Graded Polymict breccia show their own appearance and clast lithologies, although similarities and variations in detail. These two sub-units are the upper units of the Vakkejokk Breccia layer, and are most likely resurge deposited. A resurge deposit can vary greatly from place to place as described from the Lockne crater. This variation depends on factors such as the underlying topography where the resurge sediment is deposited and what is the material carried by the resurge. The deposit at drill site varies both vertical and lateral.

The places to drill the coreholes were chosen at outcropings were the Top Sandstone and the underlying Graded Polymict Breccia were exposed. The retrieved drillcores from the proposed resurge deposit show in general a fining in an upwards succession; from a in general darker (lower part) through a general lighter colored (upper part) of the Graded Polymict Breccia which transists upwards into a greenish sandstone. This sandstone could be separated into lower coarse sand, which grading upwards to fine sand about 19 cm thick, further continue up into a fine silty layer with a thickness of circa 18 cm. The latter in particular shows repeated bedding (laminated). These individual beds are approximately 2-3 cm thick, were thin, light colored silt layers repeatedly appears (recurrent) in greenish siltstone. This could indicate that the of the meteorite impact related resurging waves decreasing in force which results in water turbulence decreasing at time of deposition of the silt. The up to 40 cm thick sandstone sequence exhibit a slightly light greenish tint as seen in (figure 14A), which is likely because of the green lower Cambrian marine silt that was incorporated in connection with the resurgance. The absence of the siltstone with repeated in the Vakk_CH2A and Vakk_CH2B may be caused by the outcroppings is more eroded than the top part of borehole Vakk_CH1. At least one of the drillcores shows a sharp, or semi-sharp contact, i.e. slightly erosive (likely some cm) where the coarse sandstone transist into the overlying fine grained sandstone, allowing similarities and variations in detail. The coarse part of the sandstone expresses relatively rapid transitions into the underlying upper part of the Graded Polymict Breccia. Ormö et al. (2017, table 1) reports that at drill site, the Top Sandstone is 35cm thick which corresponds with the results at up to 40 cm presented here, and Ormö et al. (2017) report that the Graded Polymict Breccia is up to 1.5 meter. In this project the drillholes were >1,35 cm deep and, and was not drilled into the boarder of the underlying Lower Sandstone Member, which contain mega clast (fig 5G-1) named Lower Polymict Breccia. The Vakkejokk Breccia at drill site has similarities with the Lockne crater, in particular were the contact between the Loftarstone and Lockne Breccia exhibit both sharp and gradual transitions; it is described that the two extremes at Hällnäset occur ten meters apart.

All this may indicate the coarse and fine sand are transported by water and deposited out of suspension of turbidity current e.g. a resurge caused by a hypervelocity meteorite impacts. Whereas the lower part of the Graded Polymict Breccia the clasts are transported by rolling and sliding at the bottom of the putative resurge (traction flow) which was driven by an overriding suspension flow described of Ormö et al. (2017), saltation is also one of the transport mechanism of clasts and granules. The breccia is in general matrix supported, and the breccia is polymict with four clast lithologies: green siltstone-, brown-red siltstone, light gray granite and brown granite, slightly variation in details. The two main clast-types of clasts are present i.e. granite and siltstone clasts. Both brown and light gray granite clasts seen in the lower part of the Lower Polymict Breccia are intersected by thin fractures in several directions (see for example figure 14B and 15D). This could be classified as breccia in breccia structure, fractures are most likely caused by the putative impact: in the complex contact and excavation process (see chapter 3). The angular to sub-angular granite, siltstone clasts are interpreted caused as result of short transportation before deposition as seen of their angularity.

A hypothesis inferred here about the origin of the brown granite clasts is that they could be derived from the bottom conglomerate, or from the regolith which rest here and there on the basement (Thelander 1982) or the sub conglomerate at figure 5J-2. Possible the brown clast is not derived from rocks of the Linagranite suit, could be derived from some of the older. Otherwise the brown granite clast could have been have been colored by the surrounding, more from the brown matrix. What speaks against coloration from the surrounding matrix is that the brown color is penetrative and not only at the surface of the clasts, which seems that the color is in the crystals of the clasts. A hypothesis inferred here about the mechanism for concentration of brown clast is that one brown clast could have disintegrated into many smaller pieces at time of deposition. This could explain the accumulation of a swarm of brown granite; figure 13 B and figure 14B show brown granite clasts as well as brown matrix with brown small granite clasts (figure 15 and 15C). Siltstone clasts are often elongated, slightly too greatly contorted and discoid as seen at the outcropping Graded Polymict Breccia at the drill site, as well as at drillcore halves, this speak for that the silt and sand was most likely semi-solid at time of deposition. Regarding to Ormö et al. (2007) a locality close to the rim of the Lockne crater, the Loftarstone as well as the underlying Lockne Breccia have the same bulk composition. In this study interpretation has not been done regarding the bulk composition of the Top Sandstone and the Graded Polymict Breccia, such an analysis has to be studied for example by optical analysis of clast and samples matrix in thin-section.

Kulling (1930) describes that the Crystalline basement consists of granite and reddish gneissic-granite at the section between the rivulets Orddajohka and Tjäurajokk, this red gneiss-granite is likely seen at a outcrop south of drill site (figure 5I).

Kulling (1930) reports a clast of the lithology fine lime-mica slate; his clast could *in fact* be a melt fragment. No clast of the red granite of the Linagranit-suite described for instance by Witschard (1984), is for sure categorized in this project; further study is needed, for instance thin-section.

Kulling reports clasts of sandstone in the breccia, but in this project sandstone have not been seen for sure in the vicinity of the drill site, except for one possible sandstone clast found at the Top Conglomerate outcropping (figure 5B).

The clast lithologies of the crystalline clast in the breccia are likely excavated from the Precambrian basement. The siltstone clasts are likely excavated from the early Cambrian sediments. The “breccia in breccia” structures mentioned by Kulling (1964, figure 11) is not found at the drill site or in the drillcores, this clast consist of breccia which is incorporated in the Vakkejokk Breccia could be derived from a conglomerates reported in some of the formations related to the Greensstone Group or the younger groups; see Bedrock map description 30J Rensjön NW by Kathol & Martinsson (1999).
The color of the matrix varies between green, brown-red with greenish flames, dark red, brown, and dark gray (figure 15G-K). Vogt (1967) measured a bed of green siltstone is 11.5 meter thicker (i.e below Vakkejokk Breccia) in the area of Gevdnjajavri and also that bed has red siltstone in small beds within the green siltstone. These green beds containing red beds could possibly be an analogue to the brown-red matrix with greenish flames (figure 15H) found in the three cores. The darker colored matrix appear at approximately circa 80 cm depth and deeper, hovewer variation in the three drillcores.
The red round chert (figure 13H) could have its origin from the or from the Greenstone group

The finds of chert could indicate that the putative meteorite penetrated the basement down to a Perthite-Monzonite suit, Haparanda suit or Kirunagreenstone Group or some of the sub-formations eventually below a probable intrusion of Linagranite. Jaspis is reported from Kirunagreenstone (Kathol and Martinsson 1999). On the other hand an alternative is that the Vaivvancohkka – Salmmecohkka massif rest or partly rests on the gabbro and diorite carrying Haparanda suit as the location for the putative meteorite impact. Study the granule with a pearly tint (figure 15A) which could determined as a grain of labradorite. The mineral precipitation in vug spaces (figure 15F) could be a former dolomite clast. As well as the light gray granite clast (figure 13C) could possible (*in fact)* be an ultramafic clast. The possible monomineralic e.g. carrot-orange alkali feldspar grains (figure 14A) could be derived from the pegmatite veins or pegmatoidal zones. The granite clasts have likely its origin from the crystalline basement; the red, green and dark siltstone clast is most likely derived from the sand and silt (circa 20 meters thicknesses) which lying on the sea floor at time of the putative meteorite impact.
The whole breccia outcrop at drill site seems to have generally a poor sorting and homogeneity (meso-scale) both in lateral and vertical directions, this by observations of breccia exposures at drill site as well as examination of drillcores were patches of different colored matrix here and there, but the resurge deposit is however not chaotic. Most likely the sediments carried by the resurge were not well mixed; probably rafts of sediments were transported back against the newly formed crater.

7.3. Regarding the tillites and the Snowball Earth theory

The Snowball Earth theory explains that the whole Earth was covered by snow and ice 750-580 Ma. Today glacial deposits are found on all continents of the Earth (Schrag at al. 2017), and these deposits are from the time when the ice melted. Lithostratigraphic comparison between the Vakkejokk Breccia and the glacial derived Mortensenes Tillite Formation in northern Norway was discussed by Føyn (1967). He suggested that the Vakkejokk Breccia was deposited later. Study of achritachs from sediment below the Vakkejokk Breccia shows that the neoproterozoic Mortensenes tillite and Vakkejokk Breccia is not contemporaneous and that the Vakkejokk Breccia is a younger unit (Vidal 1979 as cited in Thelander (1982). The paleogeographic latitude at time of formation of the Vakkejokk Breccia formation speaks against that it has origin as a tillite (Stodt et al. 2011).

7.4. Coredrill

In addition to the results of the geological study, the test of the portable coredrill machine HILTI DD200 is evaluated as a professional diamond coredrill with a possibility to drill up to three meters drillholes. The DD 200 demands 3kW AC, so a generator is needed.

8. Conclusion

In august 1960, the 21st International Geological Congress was held in Copenhagen. In the Torneträsk-Ofoten area a pre-congress excursion was held, were participants visited the Vakkejokk Breccia at Orddajohka Kulling (1960), which shows the attraction to geologists of the Vakkejokk Breccia.

From this study the breccia shows complexity in all directions horizontal, vertical and depth, but variations in detail. However a hypervelocity impact is a very complex process as well as the products (French 1998). The drilled sandstone and breccia have great similarities with the resurge deposits described from the Lockne crater.
Further studies are needed to analyze the clasts reported in this thesis, as well as other accessory clasts and petrographic and chemical analyses in search for fragments of melt, planar deformation features or other shock metamorphic features, as well as search for meteoritic material.

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