Prediction of the degree of thermal breakdown of limestone: A case study of the Upper Ordovician Boda Limestone, Siljan district, central Sweden

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Abstract: Quicklime (CaO) is an important geological resource with a wide variety of industrial uses. It is a base chemical produced from the burning of limestone or dolomite. This process is referred to as calcination, during which the limestone is heated to temperatures of 900 °C or higher, resulting in the discharge of CO_2, leaving a yield of quicklime. The formula can be written as follows:

Limestone: $CaCO_3 + \text{heat} \rightleftharpoons CaO + CO_2$

Dolomite: $CaMg(CO_3)_2 + \text{heat} \rightleftharpoons CaO + MgO + 2CO_2$

During calcination, a pure limestone looses about 44% of its weight, while a pure dolomite looses 48%. The amount of silica, alumina and other impurities of the original rocks is therefore near doubled. Calcination may also result in a notable loss of strength leading to fragmentation of the quicklime and formation of very fine-grained powdery material, so called 'fines'. In most areas of use, high amounts of impurities and fines are undesirable. In the present case study, three drillcores (KBH 1, 2 and 3), retrieved by Svenska Mineral from the Boda Limestone in the Siljan district, Central Sweden, have been studied with regard to facies and structure to ascertain the suitability of this limestone for the production of quicklime. The Boda limestone consists of large dome-shaped carbonate mud-mounds. The mounds consist of two members; a core member and a flank member.The core member can be subdivided in two overall facies; a red mudstone facies, which is present in all three cores, and a brown core facies only found in KBH 2. The flank member, which consists of pelmatozoan wackestone and packstone, can be found in KBH 1 and 2, while KBH 3 almost entirely consists of the red mudstone. In order to correlate limestone composition with percentage of fines after calcination, the amount of fractures, the presence of stromatactis, and the overall core-recovery were described for each core. Following this analysis, nearly 200 samples were selected from KBH 1 and 2 and subjected to calcination and mechanical force in order to simulate the industrial handling and production of CaO. The produced fines where then weighted for each sample and plotted against the physical properties of each core. The results show a clear correlation between facies and the amount of fines. The red mudstone facies gave the lowest overall values, predominantly less than 10% fines. The brown core facies has more varying values, ranging from 10-60%. The flank member ranges between 20-80%. Surprisingly, the fracture frequency seems to have little impact on the amount of fines after calcination. The presence stromatactis did not have an adverse effect on fines either. It can be concluded that the planning for an optimal use of an economically important limestone occurrence is greatly facilitated by detailed knowledge regarding the facies of the limestone and other properties such as chemistry, mineralogy of impurities and micro-textures.

Keywords: limestone, calcining, lime, quicklime, Boda, Siljan, fluxstone, ore

Supervisors: Leif Johansson and Mikael Calner

Subject: Bedrock Geology

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Att förutse det termala söderfallet av kalksten: En studie av den överordoviciska Boda kalkstenen, Siljan ringen, centrala Sverige

HÅKAN OLSSON

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Sammanfattning: Kalksten är en av våra viktiga geologiska resurser och har använts genom historien, till byggmaterial, jordbruk och inom modern industri. Kalksten i alla dess former har varit en viktig del av människans kulturella och teknologiska utveckling. Ett av alla dess användningsområden är som flussmedel vid bearbetning av järnmalm; bränd kalk tillsätts när malmen smälts och binder då till de ämnen i malmen man vill separera från järnet. Detta är då främst kisel- och aluminiummineral. Bränd kalk är kalk som blivit upphettad till sådana temperaturer att CO_2 avges från $CaCO_3$. Den kvarvarande CaO är reaktiv och binder lätt till CO_2 och vatten. När CaO, på engelska kallad ”lime”, reagerar med vatten bildas släckt kalk, CaOH eller ”quicklime”.

För att den brända kalken ska vara ett effektivt flussmedel som möjligt krävs att den kan tillsättas som större stycken snarare än ett finfördelat pulver. Detta medför större krav på den kalksten som används som ursprungsmaterial till den brända kalken. Den måste kunna stå emot upphettningsprocessen och mekanisk påfrestning både före och efter bränningen. Produktionskostnaden för bränd kalk är också väldigt hög; kalken måste hettas upp till över 900 °C tillräckligt länge för att all CO_2 skall avges. När detta sker miskar massan med 44 % då CO_2 övergår till gasform. Produceras då större mängder oanvändbart finmaterial vid bränningen går mycket material och energi gott till spillo, såväl som att stora mängder CO_2 släppts ut.

I den här studien har tre borrkärnor (KBH 1-3) undersökts, upptagna av Svenska Mineral från Boda kalkstenen, Siljanringen, Sverige. Undersökningarna har omfattat studier av facies och strukturer för att avgöra huruvida kalkstenen lämpar sig för produktion av bränd kalk. Bodakalkstenen består av större domformade rev. Dessa kan delas in i två enheter; en kärnenhet och en flankenhet. Kärnenheten kan i sin tur delas in i röd lerkalksfacies och brun kärnfacies som bara påträffats i KBH 2. Flankenheten består av rasmaterial, främst i form av fragment från sjöliljor och lerkalk. Denna påträffas i båda KBH 1 och 2 medens KBH 3 utgörs av mestadels röd kalkler. Andelen finmaterial som bildats vid bränning har korrelerats med facies, sprickor, stromatactis strukturer och sammanhållningen av den upphämtade kärnan. Nära 200 prov togs från KBH 1 och 2, och utsattes för bränning, följt av mekanisk påverkan för att simulera industriell behandling. Finmaterialet som då producerats har vägts för vart prov och plottats mot kärnornas egenskaper. Resultaten visar på en tydlig korrelation mellan facies och finmaterial. Den röda kalkleren gav generallt mindre än 10 % finmaterial medens den bruna kärnfacien gav mellan 20 och 80 % och flankenheten gav mellan 20 och 80 %. Däremot hittas ingen korrelation mellan hög sprickighet och högre procent finmaterial. Stromataktis strukturer verkar ha en benägenhet att sänka andelen finmaterial något. Vid planeringen av brytning av liknade kalkförekomster kan en bättre förståelse av facies och andra faktorer vara av stor ekonomisk vikt då det kan påvisa förekomstens lämplighet.

Nyckelord: kalk, kalksten, bränd, släckt, CaO

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1 Introduction

Modern mining of geological resources bring greater demands and challenges then ever before. Environmental considerations have become greater, now spanning beyond local or regional impacts into global. It has become clear that the resources we use must be handled in a sustainable manner and the production related pollution minimized.

One of the most commonly used geological resources, together with fossil fuels and metal ores, are carbonate rocks. Various forms of limestone and dolomite have been used throughout history in virtually every culture and civilization and have always been an important geological resource. Today, limestone is defined as a sedimentary rock containing 50% calcium carbonate or higher and such rocks are widely distributed around the world. Sedimentary carbonate rocks are formed by the accumulation of organic hard parts such as shells or skeletal remains. Even when not defined as limestone, inorganic carbonates rocks may be used to produce lime. Such rocks may have formed through chemical precipitation. Other important carbonates include metamorphic rocks such as marble.

As limestone is relatively easy to work with, due to it being softer than most crystalline rocks it has been used as building materials, for sculptures and artwork.

Due to its chemical properties it has also been widely used. In agriculture it is used to fertilize soils by raising pH. Lime has been used to combat acidification of soils and lakes during the last century. In modern industry, uses include the manufacturing of paper, glass, rock wool, chemicals like calcium carbide and sodium bicarbonate and in ore processing (Fig. 1), the latter being the focus of this paper. This paper reports an attempt to characterize the thermal properties of limestones used in the production of fluxstones. Fluxstones are materials that are used to separate a desired element or compound by reacting and bounding with the undesired compounds like silicates. When processing iron ore, lime fluxstones are added to separate iron from any silica, alumina as well as phosphorus (Bates 1969 p. 160).

2 Project background

Carbonate rocks, mainly in the form of limestone, provide CaO and $Ca(OH)_2$, chemicals with a wide range of uses. The challenge is to find the optimal ways of obtaining resources. Unlike the concerns for fossils fuels, sources for CaO, or “lime” are in little danger of running dry. However, once used lime can rarely be re-used as in the case of metals that can be melted down and recycled time and time again. Further more, the energy, materials and CO_2 emissions associated with the production of lime are high. To turn limestone into lime it has to be quarried, processed into manageable sizes and heated up to temperatures over 900 ˚C. The lime can then be used for various purposes, but depending on the qualities of the limestone, it will be more suited for certain uses than others. By heating limestone, lime is produced through a process of calcining or “burning”. Provided that the P_{CO2} is very low the calcining process may start already at temperatures as low as 550 ˚C (Lide 2005). When limestone is heated to temperatures over ca. 900 ˚C, CO_2 leaves the rock as a gas at a high rate, leaving a $CaO_{(S)}$ rock behind.

$$CaCO_3 + \text{heat} \rightleftharpoons CaO + CO_2$$

Calcite Lime

$$CaMg(CO_3)_2 + \text{heat} \rightleftharpoons CaO + MgO + 2CO_2$$

Dolomite Lime Periclase

Several factors control weather the lime is suited for the use as a fluxstone or not. One of the requirements is that the limestone must retain its shape during the calcination and not disintegrate into fines. Due to the loss of the CO_2 the rock may lose cohesive strength and brake down to fines. In some cases this is not a problem and can even be an advantage, however, as a fluxstone the lime must remain in larger pieces. There are also chemical requirements. The content of other minerals such as clays or quartz grains needs to be low. The fact that $CaCO_3$ lose about half it mass when the CO_2 is lost means any impurities in the limestone is doubled in the lime.

To optimize the production of lime and to minimize the emission of CO_2 it is highly desirable to only use carbonate raw materials that, during calcination, produces a minimal amounts of fine material. This can be done using advanced methods like optical microscopy, scanning electron microscopy and calcination tests in laboratory. These methods are efficient but relatively time consuming and therefore expensive. A method based on direct observations of rocks in the quarry or of drill cores would be optimal.

Goals

- To test if its possible to directly predict the degree of thermal breakdown of limestone i.e. formation of fines by visual inspection of drill cores
- To visually describe the Boda cores on the basis of lithology, facies and structures. To experimentally test how the Boda Limestone responds to calcination and to correlate the results visually observable factors.

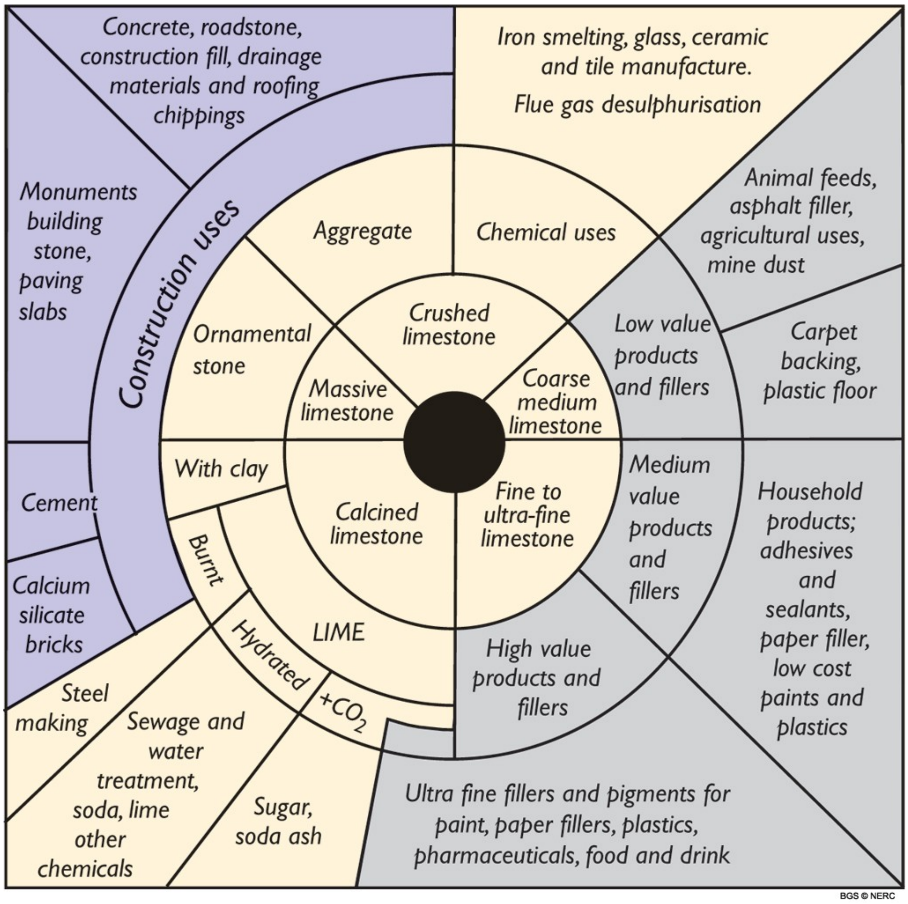


Fig. 1. Summary of common uses for limestone. From British Geological Survey; http://www.bgs.ac.uk/mendips/aggregates/stone_resource/stoneuses.html.

3 The Boda Limestone

3.1 Geological setting

The bedrock in central Sweden mainly consists of Precambrian crystalline rocks. However, in the Siljan district, Lower Palaeozoic sedimentary rocks are distributed in a circular pattern (Fig. 2 A-B). Viewed from the air this circular pattern can also be observed in the distribution of lakes in the area. This landscape is the result of a Devonian impact event about 377 Ma ago (reference). The crater or astrobleme has been estimated to measure some 65-75 km across (Henkel and Aaro 2005), however Holm et al. (2011) suggested a diameter of 90 km. For comparison, the crater formed at K-T boundary is about 200 km across. Sedimentary rocks which are believed to have once covered much of Sweden, have been eroded away when much of the Scandinavian landmass rose above sea level, exposing the sediments to weathering and erosion. The sediments are preserved only in the depressions formed by the impact. The original stratigraphy has been deformed by faults and the whole bedrock shows, in various degrees, fractures and deformation caused by the impact.

The Boda Limestone differs in many ways from the typical Ordovician limestones of Sweden (e.g. Ölandskalksten). Rather than being conformed to layers upon layers, the deposits include dome shaped mounds with morphology similar to reef (Fig. 3). However, they are not reef *sensu strictu*, as there are few reef building organisms present (cf. Riding 2002). The mounds are composed by a *core facies* making up the main carbonate build-up that rose up from the surrounding seabed at the time of deposition, presumably similar to how modern reefs develop today. Around the mounds, material from dead organisms, mainly crinoids, accumulate as debris, or *flank facies* producing a pelmatozoan grainstone (Figs. 3-4). These facies vary in colour, appearance, structural properties etc. The transition between the facies is gradual. The core facies consists of a fine grained mudstone. Fossils are scarce, but brachiopods, trilobites, even corals and other reef building organisms can be found. The latter are represented by *Eocatinopora* sp., *streptelasmatidae* indet. sp. and bryozoans, possible *Phylloporine* sp. (see Harper and Owen 1996). Pelmatozoans also occur

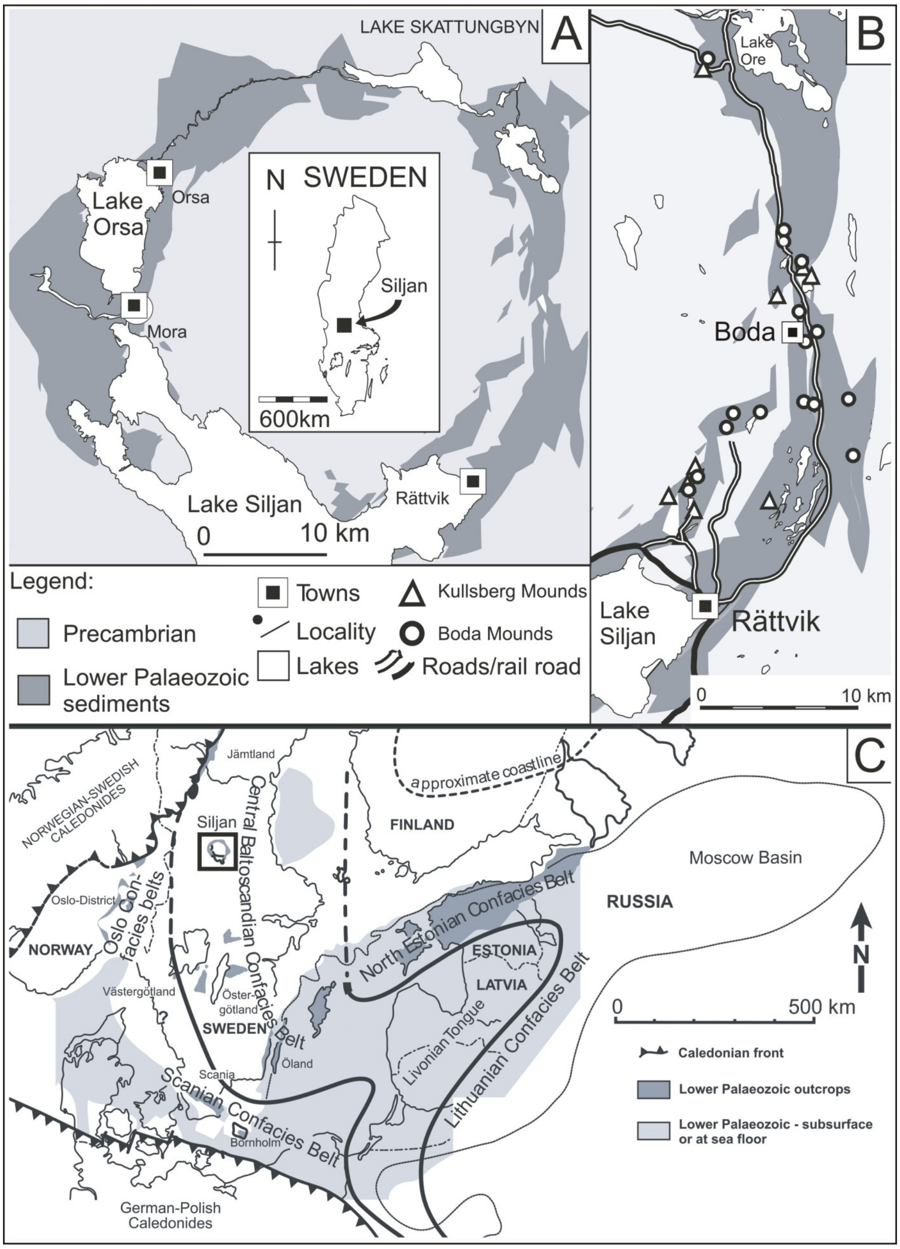


Fig. 2. Late Ordovician palaeogeography. A. geological map of the Siljan district. B. Locations of known carbonate mud mound in the area near Boda. C. Map showing the palaeogeography of the Late Ordovician Baltoscandia. Modified from Ebbestad et al. (2007).

but are the most common in flank facies.

The Boda mounds are lateral equivalents to the Upper Ordovician Jonstorp Formation (Fig. 3). The mud-mounds are more or less lens shaped and can span up to 1000 m in diameter and reach 100-140 m in thickness (Suzuki and Bergström 1999). Only the flanks show any clear stratification while the domes are homogeneous unlike most other limestones. There is however large scale fractures, faults and cavities much like the ones that can be found in the Gotland reefs. Another notable feature is the rich occurrence of petroleum trapped in cavities and fractures. Where this limestone is mined, the smell of petroleum can often be noticed. The source rock for the petroleum is the underlying Fjäcka Shale, a dark shale rich in organic material.

One of the most striking features of the core facies is the occurrence of stromatactis, an enigmatic stratified spar structure of unknown origin (Fig. 4). These structures dominate in some parts of the examined cores, making up the majority of the limestone. In other parts they are practically lacking. Despite being first described as early as 1881 by Dupont, the formation of stromatactis remains a mystery, it has not been determined whether or not stromatactis have been formed sys-sedimentary or during diagenesis. It has been suggested to be the result of frost weaving of gas clathrates (Krause 2001; Krause et al. 2004). However, this hypothesis requires that the mounds were formed in cooler waters then is generally believed.

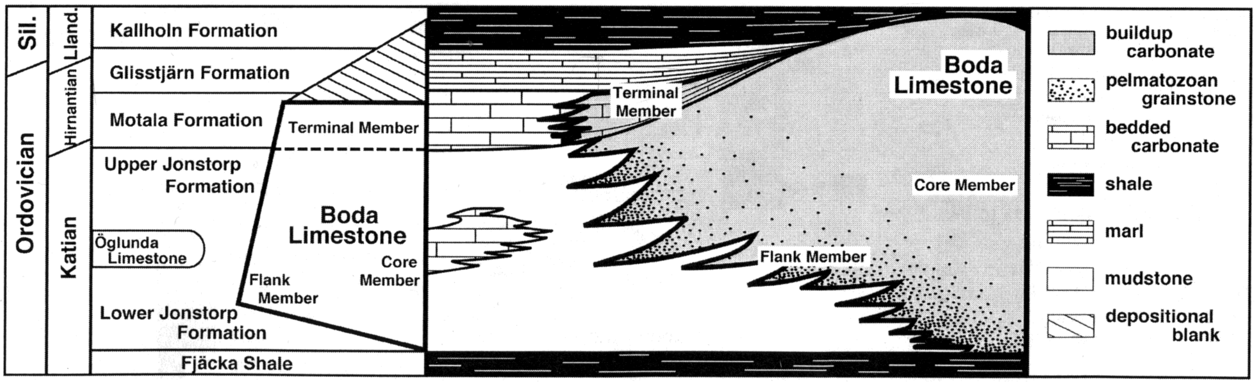


Fig. 3. Morphology of a typical Boda carbonate mud mound. The underlying Fjäcka shale is the source rock of the petroleum products found in pores and fractures in the limestone. From Suzuki et al. (2009).

3.2 Paleoecology

The Ordovician oceans had a diverse biology with molluscs, echinoderm, bryozoans, cnidarians and brachiopods being important members of the ecological communities contrary to the trilobite-dominated communities in the Cambrian. Trilobites still remained an important group in the Ordovician seas. Together with cephalopods, they make up the most common macrofossils to be found in many of the Ordovician limestones in Scandinavia.

Suzuki and Bergström (1999) described a rich trilobite fauna found in cavities.

4 Methods

This study is based on three drill cores from the Boda area, Siljan district, central Sweden (Fig. 2). The cores where collected by Svenska Mineral AB. The cores have a width of 3.5 cm and have been sawed along the centre line.

Based on the material available, no reliable correlation could be made between the cores.

4.1.1 KBH1

Core nr 1 is 60.23 meter in total length. This is the only core that includes non-sedimentary rocks. Below 46 meters it consists of brecciated crystalline rocks which are of no interest in this study. The uppermost part there is a reef like facies of white limestone followed by an interval with crinoidal flank sediments. This interval has very poor recovery and displays rust, possibly indicating pyrite.

Under the flank facies there is a consistent unit of red core facies with high recovery. No petroleum was found in this core and no signs of pyrite.

4.1.2 KBH2

Core nr 2 is 80.53 meters in length making it the longest retrieved core from the site. It is dominated by red and brown core facies interbedded with flank facies most notably in the lower third of the core.

4.1.3 KBH3

Core nr 3 is 75.53 meters in length and is almost entirely made up of red core facies. Below 15 meter petroleum occurs in great quantities. These occurrences are mainly in the form of droplets in fractures and cavities.

4.1.4 Sampling

Samples were collected for test burning from cores KBH 1 and KBH 2. From KBH 1, 43 samples where collected with one sample per meter and 144 samples with two samples per meter from KBH 2. The latter core was chosen for the more detailed study because of it is the longest core (80 m) and the most varied of the three with regards to facies.

Core number 3 was rich in petroleum with droplets of oil found in virtually every meter. The effect petroleum might have on samples when burned, is unknown. Regardless if it has a positive or negative effect, it will not be representative for the major part of the of the limestone deposit. The sparse occurrence of petroleum in core 2 was still deemed satisfactory to determine if it indeed had a notable impact on the outcome when the limestone was burned.

Selected samples were classified on bases of facies, colour, recovery and the occurrence of cracks, stromatactis structures, stylolites and petroleum. Each sample had a minimum weight of 300 grams prior to burning, which translates into a sample length around 20-30 cm of core section.

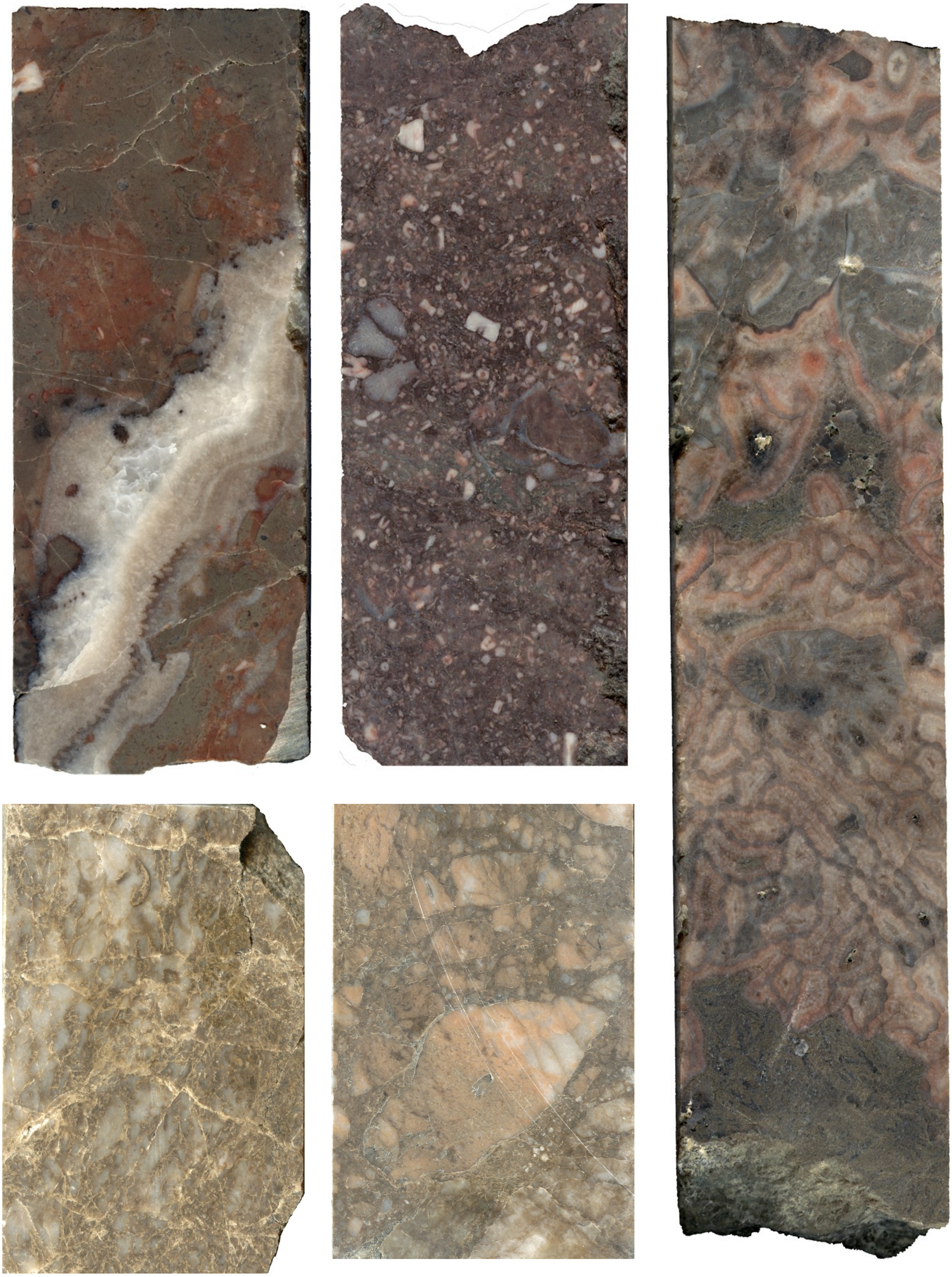
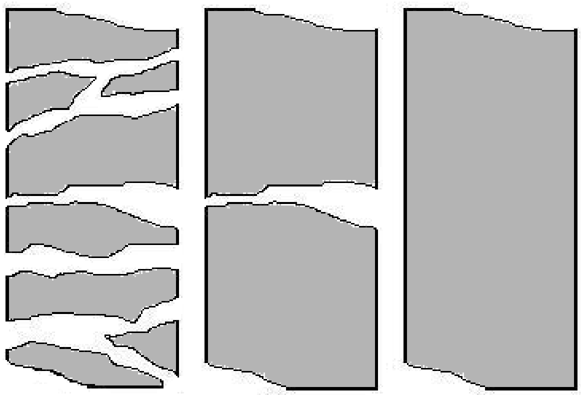


Fig. 4. Core facies make up most of the Boda Limestone and consist of two variants; red core facies (top left) and the brown core facies (bottom left). Centre top; Flank facies with crinoid fragments. Centre bottom; brecciated facies. Right; corals (*Eocatinopora sp*. surrounding possible Streptelasmatidae species, arrow) with petroleum drop-

4.2.1 Recovery

Recovery refers to what extent the core has been fragmented during drilling. Divided into a scale of three, low recovery (I) means that the core consist of pieces smaller than the width of the core 3.5 cm, medium recovery (II) means the pieces are bigger then the core width but shorter than 10 cm. Any section of the core consisting of parts over 10 cm in length are considered to have high recovery (III). See figure 5.

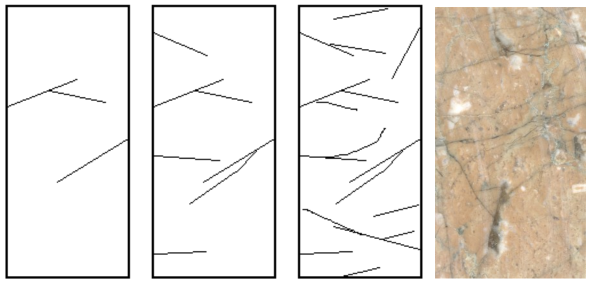


I II III

Fig. 5. Schematic figure showing different degrees of recovery of a retrieved core. Left; poor recovery (I), middle; medium (II) and right; high (III).

4.2.2 Fractures

The presence of fractures (Fig. 6) are of great interest for the quality of the limestone, where low frequencies are desirable. Low abundance (I), indicate that few or no fractures were observed. Medium (II) meaning that fractures are common and (III) that fractures are abundant.



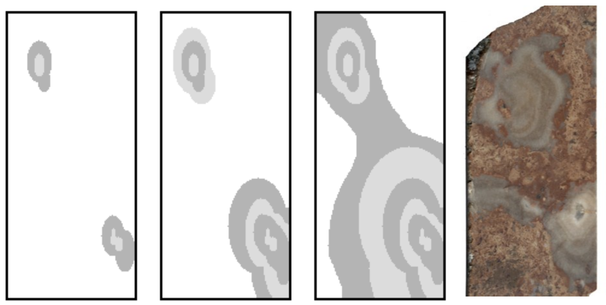
I II III

Fig. 6. Levels of fractures divided into three categories; I, II through III with rising fracture frequence and an example of a red core slab with abundant (III) fractures.

4.2.3 Stromatactis

Stromatactis (Fig. 7) structures are not common in limestones and their origin remains enigmatic. Stromatactis bears some resemblance to agate, occurring as concentric growths, occasionally with a centre cavity with larger crystals. Being present in the Boda Limestone it could be an important property.

These structures occur mainly in the red and brown core facies and only occasionally in the reddish flank sediments.



I II III

Fig. 7. Stromatactis occur in the core facies of the Boda Limestone and are most common in the red core facies. For further discussion see chapter 4.1.

4.2.4 Colour

Colour varies with facies but not entirely; flank facies can be either grey or reddish possibly do to higher carbonate content then darker flank sediments. This is probably a result of the ratio between clay minerals versus carbonate mud. Some examples can be seen in figure 4.

4.2.5 Petroleum and other structures

Various amounts of petroleum can be observed throughout drill cores KBH 2 and 3 as shown in Figure 4. Petroleum occurs in the core facies, as droplets in fractures and pores. Other structures that may affect the stability of the limestone are stylolites and brecciation (Fig. 4). Breccia is a rock formed by broken rock fragments cemented by a fine-grained matrix. Stylolites are structures that form during late diagenesis when high pressures allow $CaCO_3$ to dissolve into liquid phase (pressure solution) while other minerals like clay accumulate. Stylolite form serrated surfaces in limestones.

4.3 Limestone thermal stability

4.3.1 Calcination

To determine the thermal and mechanical stability of the different types of the Boda Limestone, nearly 200 samples were collected from KBH 1 and KBH 2. The samples were placed in a ceramic oven (Fig. 8) and heated to 1050 ˚C according to Figure 9. During this heating process CO_2 discharges from the $CaCO_3$ leaving the highly reactive CaO or lime behind. The heating process as well as cooling has been undertaken in a slow continuous matter to avoid any crackling or destruction of the samples due to thermal expansion. When the top temperature of 1050 ˚C was reach, it was held at that level for 4 hours to make sure all of the CO_2 had left the rock and that only CaO remained. After that the samples were left to cool. Both heating and cooling has been slow and continuous to avoid any fracture formation due to thermal shock expansion or contraction.

Fig. 8. The samples where placed in a ceramic furnace for heating. Each sample, weighing around 300 g, corresponds to 20-30 cm of the core and consists of one or more pieces.

4.3.2 Shaking

Once manageable, the samples were removed from the oven and placed in air sealed containers to prevent that the CaO from absorbing H_2O or CO_2 from the air. The samples where then weighed and placed in a Retsch Vibratory Sieve Shaker AS 200 (Fig. 10) with 3 sieves with 8, 4 and 2 mm grids respectively. The shaking time and amplitude can be programmed. The samples were vibrated in 1 minute on amplitude 2.5 mm followed by 2 minutes on amplitude 1.5 mm. As the samples where subjected to the mechanical stress of the shaker, any material fallout from the samples was trapped in the underlying sieves.

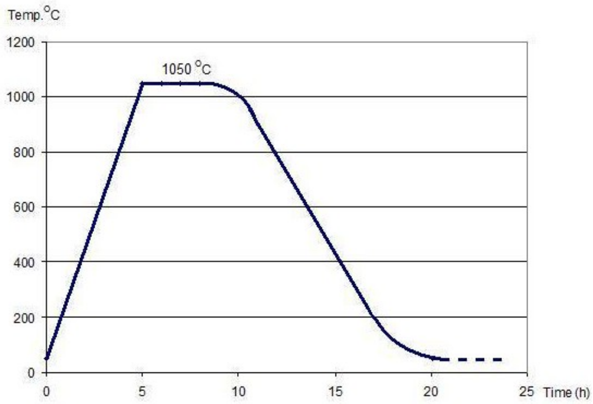


Fig. 9. The samples where gradually heated up to 1050 ^{O}C under 5 hours and held on that temperature for 4 hours. Thereafter the oven was left to cool and the samples where put in airtight containers as soon as they where manageable (60-40 ^{O}C).

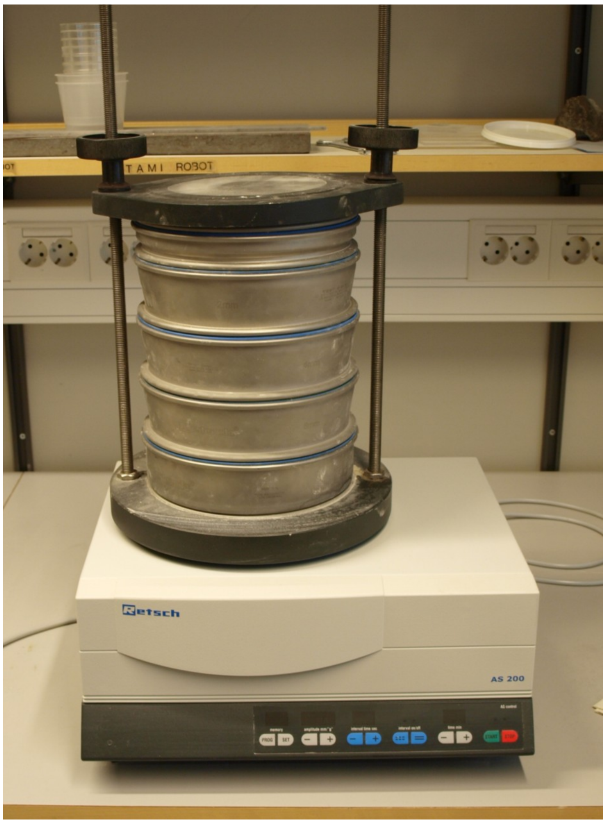


Fig. 10. All samples where weighed, placed in a Retsch Vibratory Sieve Shaker AS 200 and exposed to vibrations, 1 minute on amplitude 2.5 followed by 2 minutes on amplitude 1.5. The grids 8, 4 resp. 2 mm. and all the material passed through the 8 mm where set as fines.

All material trapped in the sieves and the bottom plate, are termed fines and measured in % of total weight. The more persistent the samples are to mechanical stress the lesser fines are accumulated. Reversely, a fragile sample would produce higher amounts of fines. Shaking protocol is shown in appendix I.

4.3.3 SEM

Some samples where studied using a SEM (Scanning Electron Microscope). The purpose was to more closely examine the different types of fractures (Fig. 11), stromatactis (Fig. 12) and stylolites (Fig. 13) to better understand their properties.

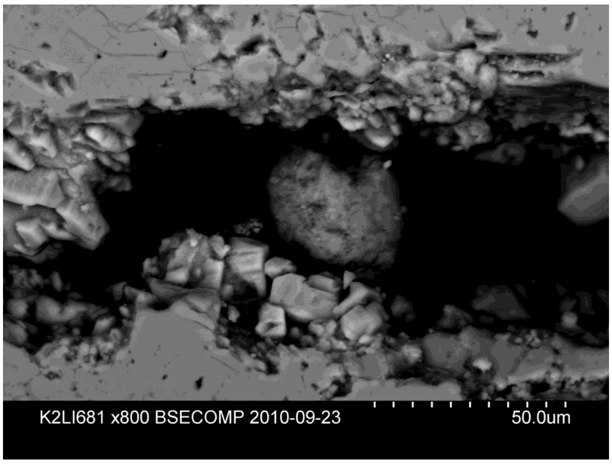


Fig. 11. Close-up crystal growth inside a fracture, indicating that these fractures could not have been formed during core retrieval.

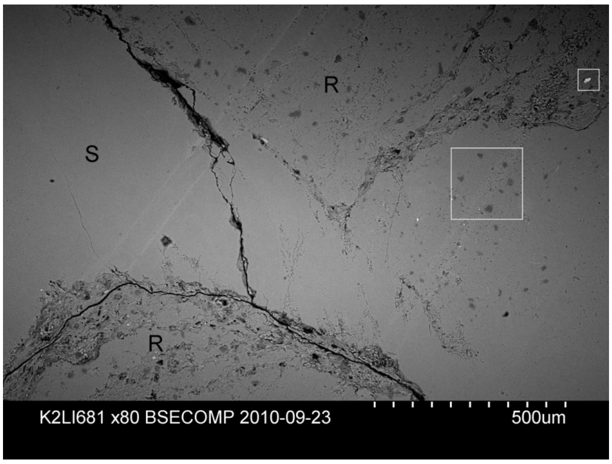


Fig. 12. Red core facies (R) and stromatactis (S). Big square indicates quartz grains, small square indicates pyrite.

5 Results

The profiles of the three cores can be seen in Figure 14. No immediate stratigraphical correlation could be done between the cores since the geographical positions of the drill sites are not known.

5.1 Fines

The variation in the amount of fines formed during the calcination of the Boda Limestone far exceeds that what was expected. The results range from less then 5% in fines, to roughly 80% fines. The results can be seen in figure 15 (KBH 1) and figure 16 (KBH 2). In figures 18 to 22, the percentage fines from KBH 1 and KBH 2 respectively, are plotted against the different factors. These include fractures (Fig. 17), stromatactis (Fig. 18), recovery (Fig 19) facies (Fig. 20) and colour (Fig. 21). Samples from KBH 1 are shown in blue and samples from KBH 2 in red. Vertical axis show percentage of fines and horizontal show the frequencies of the different factors with low (I) medium (II) and high (III) gradation.

5.1.1 Facies

Of all the factors examined in this study, facies appear to be the most important determining the outcome of fines. The facies with the lowest overall fines values is the red core facies with most fines less than 14%, while flank facies and brown core facies have higher values as can be seen in figure 15. KBH 1 also has a notably better outcome then KBH 2 even in the flank facies.

5.1.2 Recovery

Most of KBH 1 and 2 show medium to high recovery rates and only in KBH there are intervals with poor recovery. The percentage of fines varies greatly and is poorly correlated with the recovery.

5.1.3 Fracture frequence

Most samples from KBH 1 (blue) show medium to high frequence of fractures. Samples from KBH 2 (red) demonstrate a more varied frequence of fractures ranging between low to high. The amounts of fines are not well correlated with variations of the frequence of fracture since samples with medium and even high fracture frequencies, show relatively low percentage of fines (< 20%).

5.1.4 Stromatactis

Samples rich in stromatactis usually have lower per-

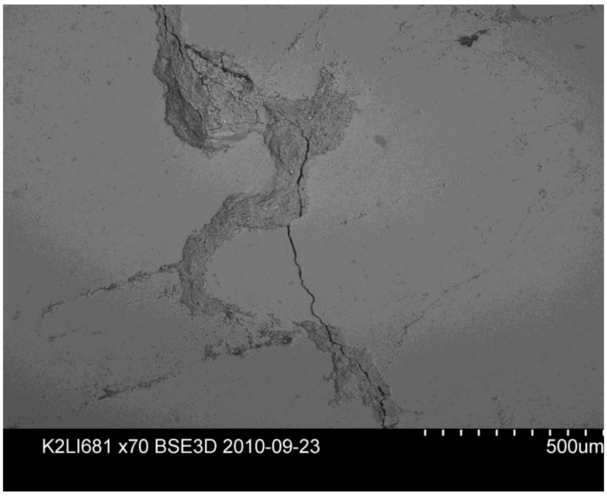


Fig. 13. SEM picture of a stylolite from the Boda Limestone. Stylolites show as jagged meandering layers of clay in cross section. Fractures often form along these layers and retrieved cores often break along them.

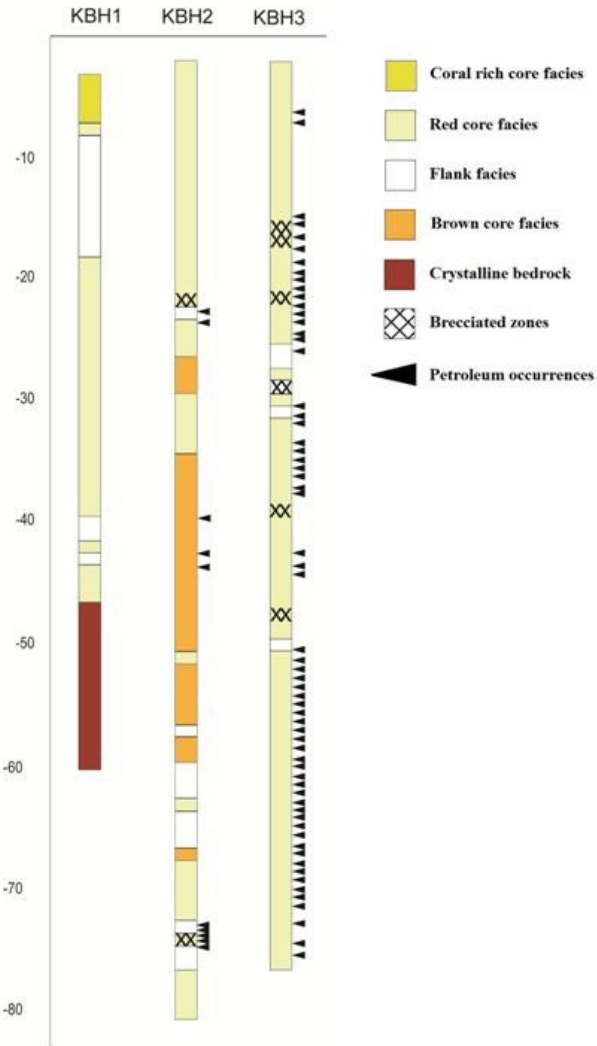


Fig. 14. Stratigraphy of the Boda drill cores. The three cores vary in length and facies composition and KBH 3 is rich in petroleum.

centage of fines than samples with few stromatactis. However this could partially be due to the lack of stromatactis in flank and brown core facies which have higher fines while being common in the red core facies. Even so, stromatactis do not produce much fine material. Scans of polished slabs and SEM studies prior to calcining determine that stromatactis contain few fractures. Scans of polished slabs, after calcining, also indicate that stromatactis have a low tendency of developing fractures.

5.1.5 Colour

Colour is the quickest and easiest way to classify the limestones. However, the colours are gradational which introduce an uncertainty. The rocks which produce the lowest percentage of fines are the red sections, mostly consisting of red core facies and the occasional reddish flank sediments, with values less than 14%.

From these diagrams it is clear that none of the parameters can be distinctly correlated with the percentage of fines. Facies seem to correlate best with the amount of fines but shows a great spread. The formation of fines is most likely controlled by more than one factor. One such factor may be the degree of re-crystallisation and content of sparrite.
Intervals consisting of these structures (see Figure 22) appear to account for some the extreme values includes the highest value found in this study. These intervals are comparably thin ranging only in 10-15 cm in thickness and occur only frequently in KBH 2 around 60-65 meters depth. When heated, these structures become extreme sensitive to mechanical handling. Fractures open to some degree, but the most fines are derived from the white areas which form 100% fines. Despite the bad quality they will have little effect on the whole deposit as they only make up a very small portion of the limestone.
The frequency of fractures, stylolites, stromatactis, recovery and petroleum does indicate to have an effect of the outcome of the percentage of fines. High values of the parameters mentioned above usually correspond to a slight rise in fines. Yet, the correlation is weak and not as notable as difference in facies.

5.2 Results SEM

The stromatactis was shown to be very pure $CaCO_3$ with no structures visible under the SEM (Fig. 13). The chemistry across the dark coloured fractures appeared to be filled with very pure $CaCO_3$. Visually open fractures seen in the retrieved cores showed sign of mineral filling by various minerals in the SEM. This is relevant as to show how the rock reacts to drilling meaning it can withstand mechanical stress to a degree without developing fractures. This might suggest why the overall recovery is good despite the many frac-

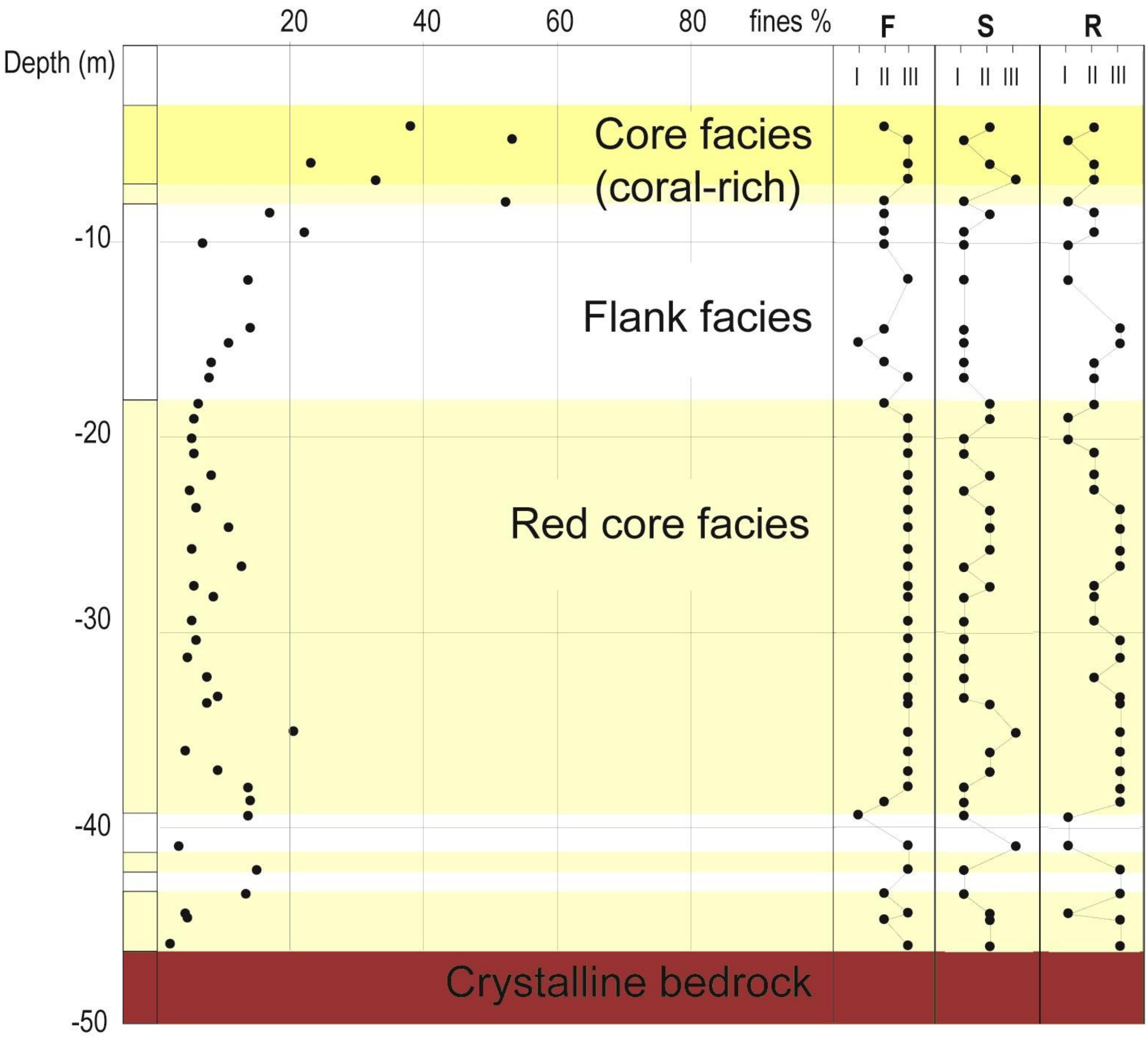


Fig. 15. Results for KBH 1. The amount of fines mainly lies below 20%. Right side indicates estimated levels of fractures, F, stromatactis, S and recovery, R.

tures. The fractures were mainly filled by calcite but also a undetermined K, P and Al based mineral (Fig. 12). Scans of the red core facies also revealed high amounts of quartz grains in the matrix (Fig. 13). As quartz has been a problem in other lime stones, this validates further studies to determine the quantity of quartz in different facies. Stylolites contain clay mineral and fractures are prone to form along these structures (Fig. 14) as well as breaking points in the retrieved cores.

6 Discussion

Since the calcination of carbonate rocks is a very energy consuming process with large emissions of CO_2 it is highly desirable to optimize the entire production line from the quarry to the final product. One important step along that line is the calcination of the limestone and the potential breakdown of the stone to fines. Therefore the perhaps most effective way to minimize the energy need and the CO2 emissions is to select the best raw material for calcination. This includes finding material with high chemical purity and thermal stability. An optimal limestone i.e. thermally stable, will retain it shape through the calcination and not disintegrate to fine materials (fines).

In order to find thermally stable limestones we can do systematic calcination laboratory tests of drill core material but it would be even better if “good and bad” limestones could be visually recognized already in the quarry by means of texturally easily observable factors. Of the five studied factors only one, facies, seems to be clearly correlated with the thermal breakdown of limestones. The others i.e. colour, fracture frequency, stromatactis abundance and core recovery show none or only weak correlation with the amount of fines produced during calcination. Red core facies and some brown core facies rocks show low percent-

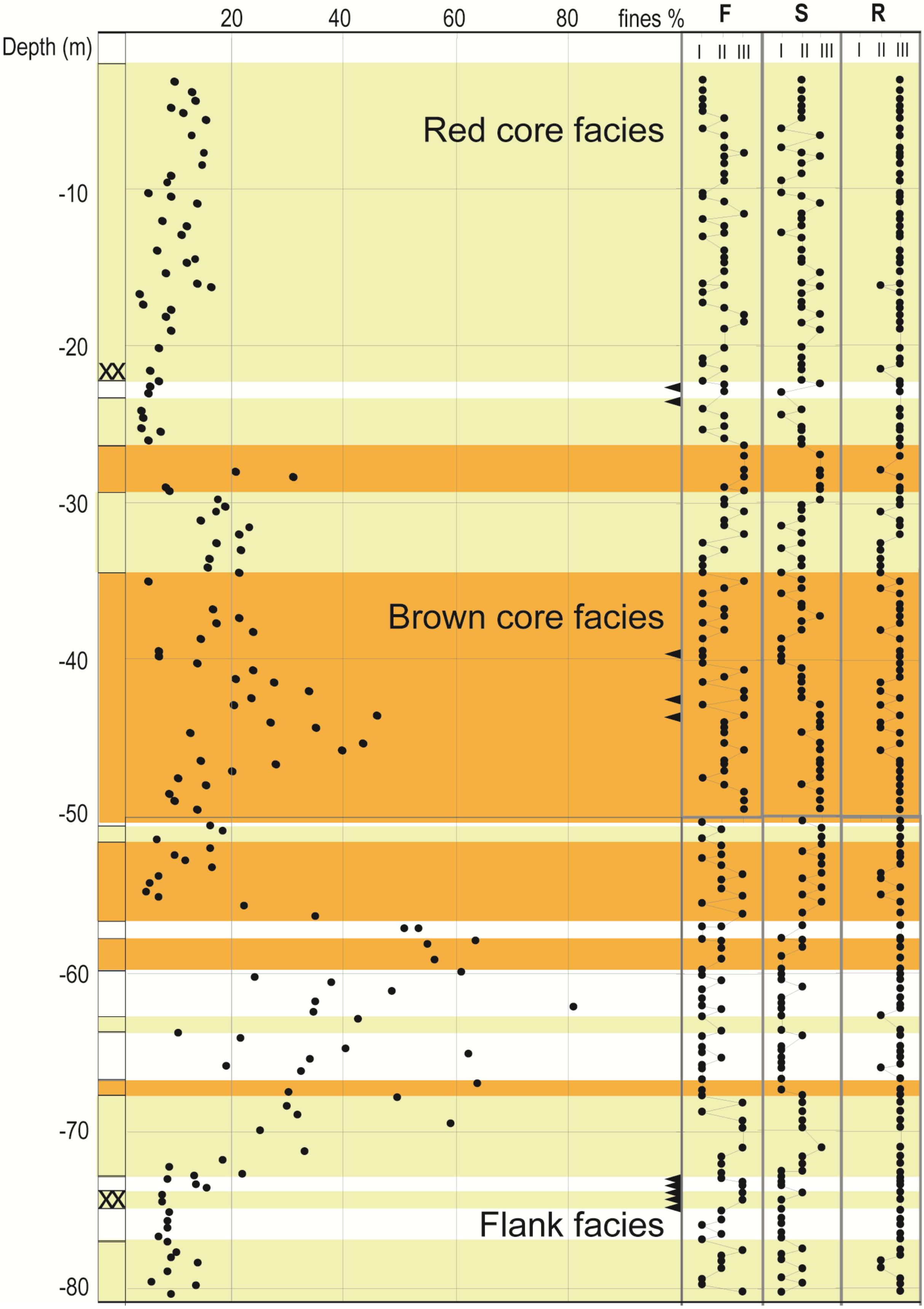


Fig. 16. Results for KBH 2. The amount of fines lies below 20% in most of the red core facies. Levels are higher in flank and brown core facies. Right side indicates estimated levels of fractures, F, stromatactis, S and recovery, R.

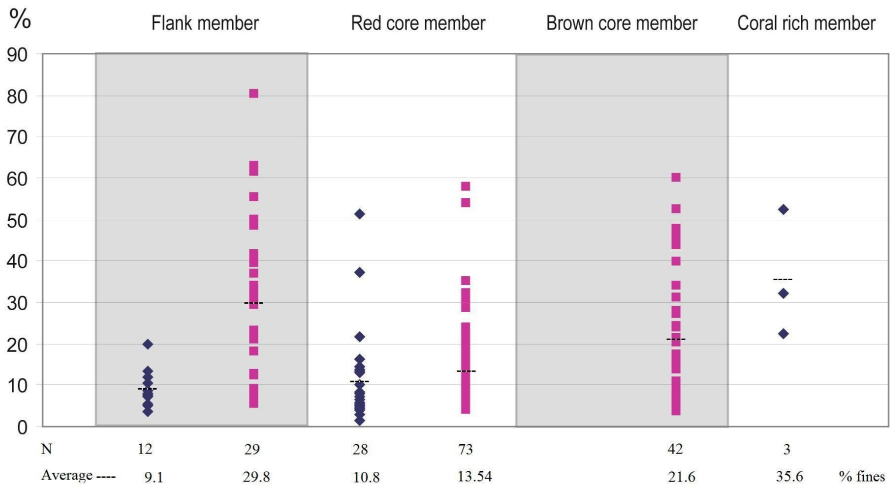


Fig. 17. Correlation between fines (%) and facies. The red core facies has the lowest amount of fines. Samples from KBH 1 are shown in blue and samples from KBH 2 are shown in red.

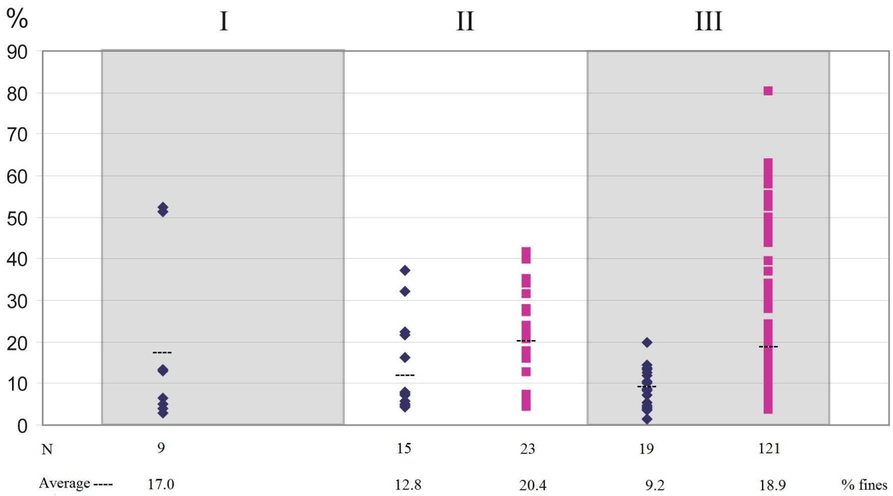


Fig. 18. Correlation between fines (%) and level of recovery. Most of the cores displayed medium to high recovery and can not be correlated to level of fines. Samples from KBH 1 are shown in blue and samples from KBH 2 are shown in red.

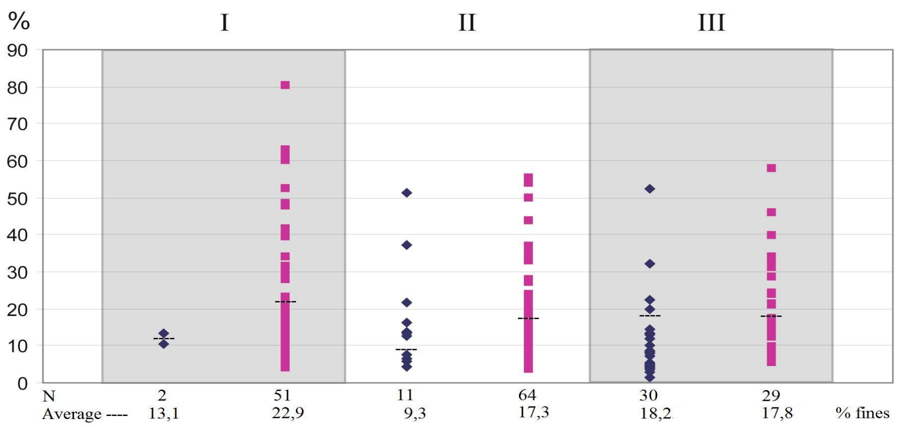


Fig. 19. Correlation between fines (%) and level of fractures. High levels of fractures does not result in any notable elevation of fines. Samples from KBH 1 are shown in blue and samples from KBH 2 are shown in red.

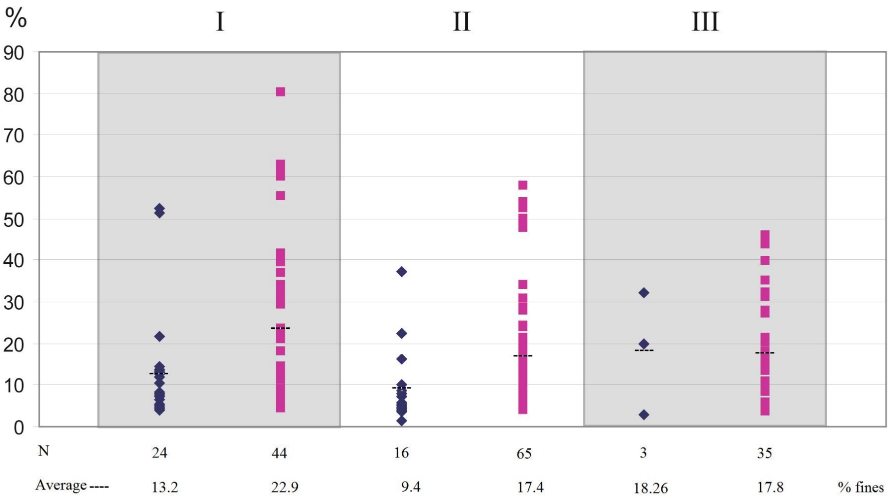


Fig. 20. Correlation between fines (%) and level of stromatactis. High levels of stromatactis correlates with slightly lower levels of fines. Samples from KBH 1 are shown in blue and samples from KBH 2 are shown in red.

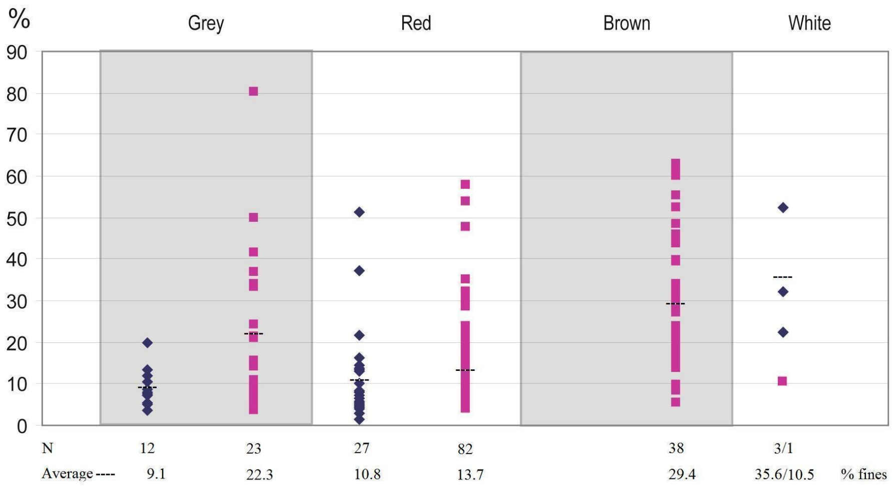


Fig. 21. Correlation between fines (%) and colour. Brown colour correlates with higher levels of fines . Samples from KBH 1 are shown in blue and samples from KBH 2 are shown in red.

Fig. 22. Macro structures resembling forms of possible reefbuilding organisms (left) loose their cohesion when heated (right) and account some for the extreme values in KBH 2.

ages of fines (12%) while flank facies and some brown core facies rocks show considerably higher fines values (20%). The reason behind this is probably that the flank facies rocks consist to a high degree of fragments cemented by calcite (sparite) that is prone to break down. In limestone from Gotland there is a clear correlation between the amount of sparite and formation of fines (Sandström 2010) with the highest fines values in rocks that formed from material eroded from the reef structures.

Fracture frequency was suspected to be an important factor correlated with the amount of fines but it turned out not to be the case. One exception is between 42-48 m in KBH2 where high levels of fines are correlated with high fracture frequency. The reason for overall weak correlation could be that limestone with calcite filled sealed fractures show approximately the same thermal stability as unfractured limestone. This is in contrast to results reported by Johansson (2011) where it was demonstrated that sealed fractures were reopened when heated. It is also possible that the average width of the fractures is important, with wide fractures more prone to reopen during calcination.

Stromatactis consists of pure calcite and resembles the sparite domains in some limestones but do not show the same tendency to be sites of fracturing as sparite does. This could possibly be due to the much more fine-grained structure of the calcite in stromatactis than in the sparite and to the crystallographic orientation of the calcite crystals. The thermal weakness of the sparite is clearly a result of straight, long and symmetrically oriented grain boundaries (i.e. granoblastic texture) (Johansson 2011) in conjunction with the thermal expansion during heating. Finally the core recovery factor shows a weak correlation with fines in the uppermost part of KBH1 and the section 42-48 m in KBH2. On the other hand there is no correlation found between 58-70 m in KBH2 which is the section with the highest fines values. The recovery factor is most likely dependent on the frequency of planar homogeneities such as stylolithes and thin clay rich layers. The limestone between these surfaces may be of high quality with respect to thermal stability. In the study by Johansson (2011) an increased frequency of micro fractures along stylolithes were noted but the overall importance of this for the formation of fines is not known. The results clearly shows that it is not possible with any high degree of certainty to predict the formation of fines based only visual observations in field or of material from drill cores. The most efficient way to predict formation of fines is to perform calcination experiments in laboratories. That method will give the most reliable results. But nonetheless, recognition of facies type of the limestone can be used to minimize the out take of flank facies rocks for calcination.

As several demands must be met from the source material to produce lime of the right quality many factors need to be taken into account. There must be a high chemical purity in limestone or dolomite with as little clay, quartz or any other silica or alumina content as possible.

Also important is that when the lime is produced and handled it must retain its physical shape, meaning it must not degrade into powder or fine material i.e. fines. Hence, determining the factors that may affect the outcome of fines will be crucial for lime production.

There is a high amount of fractures in the Boda Limestone. It seems however that the Boda Limestone still maintains high strength and presumably also is relatively resistant to mechanical stress. This could very well be a result of many fractures being healed or partially filled by calcite mineralisation gives the limestone a greater cohesion.

Another concern was the presence of stromatactis structures in the examined limestone. It was suspected that these occurrences might have a negative impact on levels of fines in the end product. Usually sparite and other carbonate crystallisation react to calcining by breaking down into fines. However, there is nothing in this study that indicates such an outcome, as high frequence of stromatactis did not correlate with high percentage of fines. In fact the stromatactis material did not break down into fines.

More then any other factor, facies seems to be the most important in deciding the outcome of fines.

7 Conclusions

The Boda Limestone is made up by dome shaped mud mounds up to 1000 meters in width and 100 meters in height. The mound itself consists primarily of a red mudstone facies as well a less dominant brown core facies. Flank facies intermingle around the surrounding slopes.

The examined cores present a notable scarcity of fossils, indicating a paleoenvironment with low biodiversity and species richness as far as the macro fauna is concerned. However, other studies have reviled high concentrations of trilobites found in mound cavities and caverns.

Simple visual examination of the cores can not be used to predict the outcome of fines after calcining other then determining facies; the dominating red core facies also seems to be the most appropriate for the production of lime, with average of 12% fines. The flank facies has the highest values and also a varying content of carbonate as some parts has higher clay content.

8 Acknowledgements

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Appendix I

Sample	k2l9			Pre-burned	Pre-shake	first	second
Depth (m)	68,82	69,06	30,6			shake	shake
weight (g)	213,6			3,0	3	9	9
Program	p5p6			P5 = 1 minutes amp. 2.5		P6 = 2 minutes amp. 1.5	
		Weight 2nd shake					
	Sieve	Sieve and	Material weight	%			
	weight	material					
sieve 8mm	435,6	583,2	147,6	69,1			
sieve 4mm	403,6	413,2	9,6	4,5			
sieve 2mm	374,9	386,2	11,3	5,3			
bottom	339,9	384,4	44,5	20,8			
Sum	1554	1767	213	99,7			
difference		-0,6	0,6				
			% Sum fines	30,6			

Appendix I. Example of protocol from a sample taken from KBH2.

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