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Surface weathering of rapakivi granite outcrops – implications for natural stone exploration and quality evaluation

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Abstract. Implications of surface weathering of rapakivi granite outcrops for natural stone evaluation were studied in the Wiborg rapakivi granite batholith in southeastern Finland. The study was performed as field mapping, comprising the whole batholith and as detailed investigations on selected outcrops. The Wiborg batholith is composed of wiborgite, pyterlite, even-grained rapakivi granite, porphyritic rapakivi granite, porphyry aplite, and gabbro-anorthosite. Wiborgite is the main rapakivi granite type. Weathering affects coarse-grained rapakivi varieties: wiborgite, pyterlite, and porphyritic rapakivi granite. Weathering occurs as surficial weathering of outcrops and randomly along subhorizontal and subvertical fractures, and varies in intensity. In the weathered upper parts of the outcrops the colour of the stone is altered and soundness of the stone diminished, which has a significant impact on the natural stone evaluation. In rapakivi granite areas, subsurface evaluation methods, by which the weathered surface part of the outcrops can be recognized, should always be used. Development of subsurface methods is required in order to make them more applicable in the evaluation of natural stone in areas with weathered rock.

Key words: natural stone, dimension stone, weathering, rapakivi, granite, exploration, Finland.

INTRODUCTION

According to the European standard EN 12670, natural stone is defined as a piece of naturally occurring rock. A natural stone product is a worked piece of naturally occurring rock used in building and for monuments. Dimension stone is another term used synonymously for natural stone for architectural purposes.

Rapakivi granites are by far the most important raw material for granitic natural stone in Finland. Almost 70% of all granite produced in Finland consists of rapakivi granite. Being anorogenic and not deformed, rapakivi granites are highly potential for natural stone, and the demand for new stone qualities from the rapakivi areas is continuous. While the produced granite is sound and intact, a typical feature of rapakivi granite is the distinct surface weathering of outcrops, so-called “grusification”. This special type of weathering can extend so deep into the rock that the first production layer from the outcrop surface down can in the worst case be unusable as natural stone. Hence, from the economic point of view it is very important to evaluate the amount of outcrop weathering during the exploration process. Consequently, weathering plays a central role in the exploration of natural stone and quality evaluation in rapakivi areas, especially regarding the assessment of the appearance and soundness of stone.

The aim of this paper is to discuss the implications of surface weathering of rapakivi granite for the exploration and quality assessment of natural stone. The study is performed as a batholith-scale field mapping and as detailed investigations on selected outcrops in the Wiborg rapakivi granite batholith in southeastern Finland.

RAPAKIVI GRANITES

Rapakivi granites are defined as A-type granites characterized by the presence, at least in the larger batholiths, of granite varieties showing rapakivi texture (Haapala & Rämö 1992). Rapakivi granites were first defined in Finland already at the end of the 1800s, but today similar granites are known in several other areas, e.g. Sweden, the Baltic countries, Russia, the Ukraine, Greenland, Canada, the United States, Brazil, Venezuela, Botswana, and Australia. Rapakivi granites occur as discordant intrusions, cutting through an older deformed metamorphic bedrock, and are not affected by a subsequent ductile deformation. A typical rapakivi texture consists of plagioclase-mantled alkali feldspar megacrysts (ovoids) and two generations of quartz and feldspar. Most rapakivi granites are of Proterozoic (ca 1800–1000 Ma) age but are also found from Archaean (ca 2800 Ma) and Phanerozoic (400–50 Ma) domains.

Incipient or aborted rifting has been suggested as the tectonic environment for many anorogenic granitic suites. Extensional tectonic setting has been prevailing during the emplacement of rapakivi granites, as indicated by the associated dyke rocks and previous shear zones. Rapakivi granite magmatism is often bimodal. Diabases, gabbros, and anorthosites occur together with rhyolite, granite, and syenite. Magmatic underplating is a probable mechanism for the generation of the silicic-mafic association. This involves partial melting of the upper mantle and lower crust in response to thermal perturbations associated with underplating. The partial fusion and upwelling of mantle material caused partial melting of the crust, producing rapakivi granite magmas (see further Rämö & Haapala 1995, 1996; Selonen et al. 2005; Lukkari 2007).

Finnish Proterozoic rapakivi granites occur as four major batholiths and several smaller batholiths and stocks in southern Finland (Rämö & Haapala 1995) (Fig. 1). The large Wiborg rapakivi granite batholith in southeastern Finland (Fig. 1) consists of five granite types: wiborgite, pyterlite, even-grained granite, porphyry aplite, and porphyritic granite, of which wiborgite is the most common granite type (see also Simonen 1987) (Fig. 2). Two of the four major batholiths are sites for natural stone production (Selonen & Härmä 2003). “Balmoral Red fine-grained” and “Balmoral Red coarse-grained” are traditional Finnish stones produced in southwestern Finland. Bright red rapakivi granites are exported globally and used in exteriors and interiors, as well as for monuments. “Carmen Red” and “Eagle Red” are red rapakivi granites, and “Baltic Brown” is a brown variety extracted in the Wiborg batholith. These stones are coarse-grained rocks with a typical rapakivi texture of large round K-feldspar ovoids, with or without a plagioclase rim. The rapakivi granites from the Wiborg batholith are produced in a large scale and are often globally used in projects demanding large amounts of homogeneous material. Rapakivi granites are quarried as natural stone also in other countries, but in much smaller quantities than in Finland.

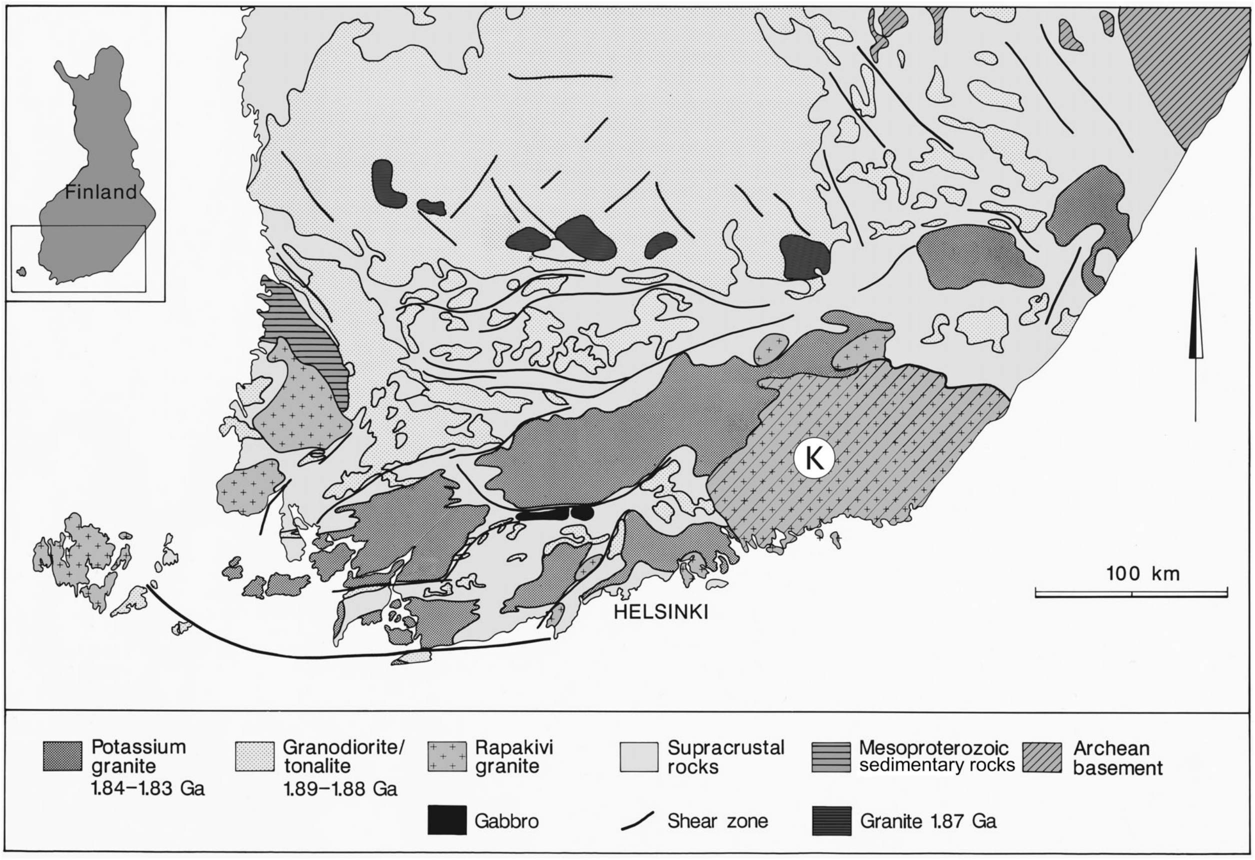


Fig. 1. The four major batholiths with Finnish rapakivi granites. The Wiborg rapakivi granite batholith is marked with “K”, which is also the study area. Modified from Simonen (1980), Ehlers et al. (1993), and Korsman et al. (1997).

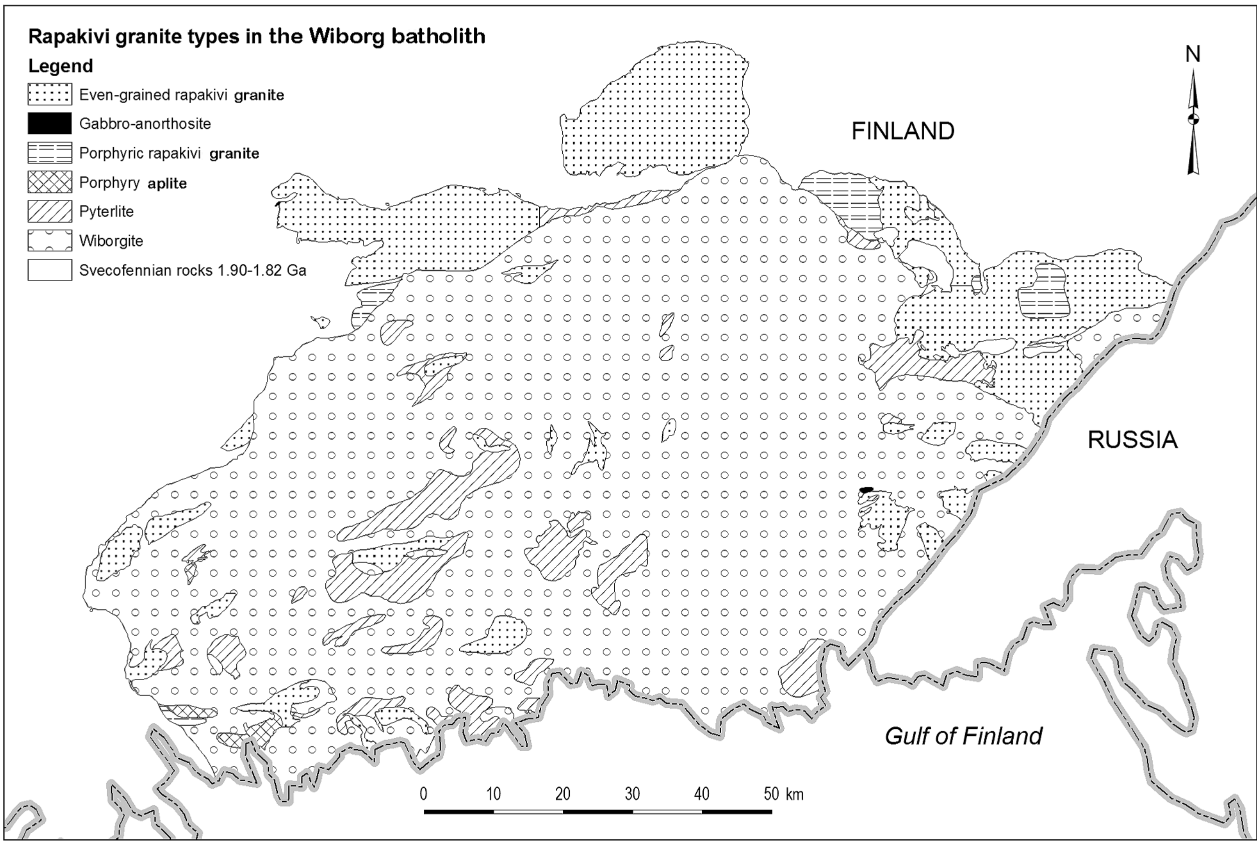


Fig. 2. Distribution of the rapakivi granite varieties in the Wiborg batholith. The map is based on this study and on Simonen (1987).

NATURAL STONE EVALUATION

Criteria for good natural stone

The three most important criteria for suitable natural stone are the market demand, the appearance of stone, and the soundness of stone. The market demand indicates that the stone has a value on the international market place for stone. Even if the stone would otherwise be suitable for production, it has no value without a demand from the market, which in turn depends on prevailing architectural style and fashion.

The aesthetical properties of stone are essential when selecting natural stone for architectonic purposes. The appearance of stone is defined by its colour, pattern, and structure (e.g. Bradley et al. 2004). Natural stones can be monochromatic, composed of one colour or polychromatic, comprising several colours. The one-coloured stones (most common colours being red, brown, and grey) include, e.g. rapakivi granites and other granitic stones, while the multicoloured stones consist of, e.g. migmatites, gneisses or gneissose granites, and marbles with a vivid and strong design. The structure of natural stones varies from even-grained or porphyritic to migmatitic. Natural stones are categorized in price by colour, where more limited colours such as blue, yellow, and black, are the most highly priced.

The colour of monochromatic stones, such as rapakivi granites, must be homogeneous across the deposit. All kinds of colour variations, stripes, inclusions, clusters of minerals, or veins are regarded as defects, and are not accepted in first class stone. In contrast, a suitable variation in colour is sought after in the polychromatic stones and more variation in appearance is accepted.

A deposit of natural stone must have a suitable pattern and spacing of fractures in order to be an object for extraction. The required fracture spacing is defined by the future use of the stone and by the block size constrained by the processing machinery. For instance, a suitable size of quarry blocks for modern gang saws varies as follows: 2.40–3.00 m × 1.30–1.90 m × 1.00–1.40 m. This implies that the spacing of the natural fractures on outcrop must be more than 2–3 m. This criterion is especially important for the rapakivi granites, because they are typically produced in a large scale with large block sizes.

The character of the fracturing is also important while assessing the soundness of a stone. The macroscopic fracturing must be sparse enough for extraction, but in addition, the stone material itself must be intact and free from cracks and microfractures. When used in construction industry the stone must satisfy strict physical and mechanical durability requirements. These properties, including the microscopic soundness, are measured in certified laboratories by standardized methods (e.g. EN standards inside the European economic area). For the quality requirements of natural stone, see further Shadmon (1996), Selonen (1998), Primavori (1999), Selonen et al. (2000), Lorenz & Gwosdz (2003), and Bradley et al. (2004).

Assessment of the appearance and soundness of stone

The appearance and soundness of stone are evaluated by different methods at different stages of the exploration process and during production. The standard exploration process includes a regional-scale prospecting and detailed site investigations (Luodes et al. 2000; Selonen et al. 2000). During the regional stage, the appearance and soundness are observed on the outcrop surface by visually defining the outlook of the stone and the spacing of the fractures. In the most promising prospects sampling can be done. During detailed investigation, the outlook and the fracturing are precisely defined and samples for aesthetical evaluation and for laboratory tests are taken. Ground penetrating radar (GPR) and core drilling are used for further assessment. The same methods are used during production and quarry development. The assessment of natural stone has been discussed in Selonen (1998), Taboada et al. (1999, 2006), Loorents (2000), Luodes et al. (2000), Selonen et al. (2000), Härmä et al. (2001, 2005, 2006), Heldal & Arvanitides (2003), Luodes (2003), and Selonen & Heldal (2003).

RAPAKIVI WEATHERING

The weathering of rapakivi granite has been known in Finland for over a hundred years. It has been studied since the beginning of the 19th century and a variety of explanations for the special type of weathering have been presented. Rapakivi granite weathers down to crumbly rock or to sharp-edged grit. This type of weathering is known as “grusification” and it comprises both mechanical and physical processes (Kejonen 1985).

The first theories implied that the disintegration could be caused by a chemical weathering of oligoclase in granite. Sederholm (1891) noted that the typical rapakivi texture is more prone to breakdown of mineral grains than, e.g. an even-grained texture. Eskola (1930) suggested that the main reason for weathering is the simple texture with smooth and straight contacts between the mineral grains. He also argued that microsheeting loosened the texture, after which the chemical weathering began to decompose Fe-rich minerals. He pointed out that only the coarse-grained rapakivi varieties and the rapakivi types which contained rather large amounts of dark, Fe-rich minerals were weathered. Furthermore, the most complete weathering could be found in outcrops on southward slopes, best exposed to sunrays.

According to Kejonen (1985), two main types of rapakivi weathering can be discerned. The most common type is the disintegration of matrix surrounding the K-feldspar ovoids, where the ovoids themselves remain less weathered. The other one is caused by microsheeting that intersects randomly all minerals and develops subconformably to the rock surface or to the primary subhorizontal fractures. Weathering is also most intense along fractures, and the spatial variation of weathering is connected with the structure and texture of granitic magma (Kejonen 1985).

The results of the earlier studies on rapakivi weathering can be summarized as follows (Kejonen 1985). “Grusification”, i.e. rapakivi weathering affects mostly coarse-grained rapakivi granite types, in particular wiborgite. Dark varieties of rapakivi with a higher content of amphibole and mica have a higher tendency to weather than light varieties. Strongly weathered horizontal or vertical zones can be found within intact zones. Usually, weathering is caused by tectonic movements affecting the texture of granite. Weathering is a slow process and dates often back to preglacial times.

STUDY AREA AND METHODS

The study area is located in southeastern Finland and comprises the Wiborg rapakivi granite batholith (Fig. 1). Studies on the weathering of the rapakivi granite outcrops included field mapping, covering the whole batholith and detailed investigations on selected outcrops. During the study the potentiality of the rocks for natural stone was also evaluated.

Regional investigation

A total of 1570 rapakivi outcrops were studied during the field mapping. Besides the rock type, the texture, colour, appearance, homogeneity, and soundness of granite were visually observed. During the mapping more attention was paid to wiborgitic and pyterlitic granites, as they are the most weathered rapakivi varieties and have the highest potential for natural stone. The study was focused on the uppermost parts of the outcrops and on the early stages of the weathering phenomena.

Detailed investigations

Detailed investigations were executed along cleaned traverses on selected outcrops (Fig. 3). The selection of outcrops was based on the representativeness of the weathering phenomena and on the potentiality for natural stone. The spacing of macroscopic fractures was measured. The general colour, colour variations, and texture of rapakivi granite were visually observed. Subsurface soundness was investigated along the traverses with GPR and core drilling (cores approx. 40 mm in diameter). The soundness and variations in appearance and colour were logged in detail from the drill cores with paying special attention to the surface parts of the cores.

Sampling

A total of 341 granite samples were collected during the field mapping and detailed investigations using a hand-held diamond saw. Resin impregnated preparations were made from selected samples in order to verify the weathering phenomena macroscopically observed on outcrops. The resin contained fluorescent, UV-light reflecting powder for the study of microfractures and cracks (e.g. Nishiyama & Kusuda 1996). Besides the impregnated preparations, thin sections were made from the samples.

RAPAKIVI GRANITE TYPES AND WEATHERING ON OUTCROPS

The Wiborg rapakivi granite batholith consists of five granite types: wiborgite, pyterlite, even-grained granite, porphyritic granite, and porphyry aplite (Fig. 2).

Wiborgite

Appearance and soundness of wiborgite

Wiborgite ("normal rapakivi") is the main rapakivi granite type in the Wiborg batholith. It has a typical rapakivi texture with alkali feldspar megacrysts (ovoids) mantled by plagioclase. The megacrysts are 1–10 cm in diameter, on average 2–4 cm. Areas with 1–2 cm ovoids can be discerned within wiborgite. The thickness of the plagioclase rim ranges within 1–5 mm. The amount of ovoids varies, occasionally they can be very scarce, but mostly they are evenly dispersed. In places, the size of ovoids is bimodal, with large and small ovoids occurring together. Smaller ovoids are more common than large ones. In few cases, the megacrysts lack the plagioclase rim. In wiborgite, the matrix between ovoids amounts to about 25–30% of the rock.

The colour of wiborgite varies, sometimes on one and same outcrop. Generally, it is brown, reddish-brown, or greenish-brown. Less common colours include light brown, dark brown or dark green. Dark-coloured wiborgite is defined as a special rapakivi variety, where the matrix is dark green, dark grey or dark brown. The minerals of wiborgite include quartz, K-feldspar, plagioclase, biotite,

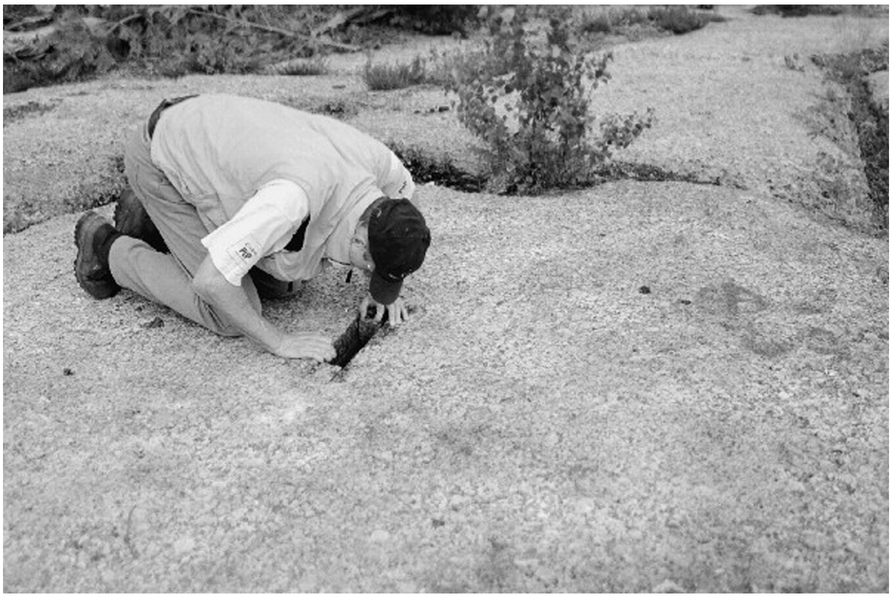


Fig. 3. Sampling was done with a hand-held diamond saw on a cleaned traverse during detailed site investigations. The sampling produced specimens approx. 7 cm in height and 20 cm in length (see Fig. 7a).

and hornblende. Dark-coloured wiborgite is richer in plagioclase and hornblende than normal wiborgite.

The macroscopic fracture pattern in wiborgite is orthogonal, with fractures both open and closed (Fig. 4). The main fractures are often open. On average, the outcrop fracturing is sparse, with at least 2–3 m spacing of horizontal and vertical fractures. According to core drilling the average horizontal spacing is 3 m. Wiborgite is highly potential for natural stone.

Weathering of wiborgite

Weathering of wiborgitic rapakivi granite varies in intensity from almost unweathered rock to total disintegration of rock (cf. Fig. 6b). In general, the upper surface parts of outcrops are weathered down to a depth of 1–2 m on average. In places, wiborgite is weathered on a single outcrop with nearly intact and weathered parts mixed randomly together. Weathering was also observed along subhorizontal and subvertical fractures and zones deeper in outcrops (Fig. 5). The colour of the rock on the outcrop surface often corresponds to the colour of a weathered rock, having paler and sometimes rustier tints than the true colour of the fresh rock.

Pyterlite

Appearance and soundness of pyterlite

Pyterlite is a porphyritic rapakivi granite variety with rounded, densely dispersed K-feldspar megacrysts 2–3 cm

Fig. 4. Typical orthogonal fracture pattern in wiborgitic rapakivi granite. Southeastern part of the Wiborg batholith.

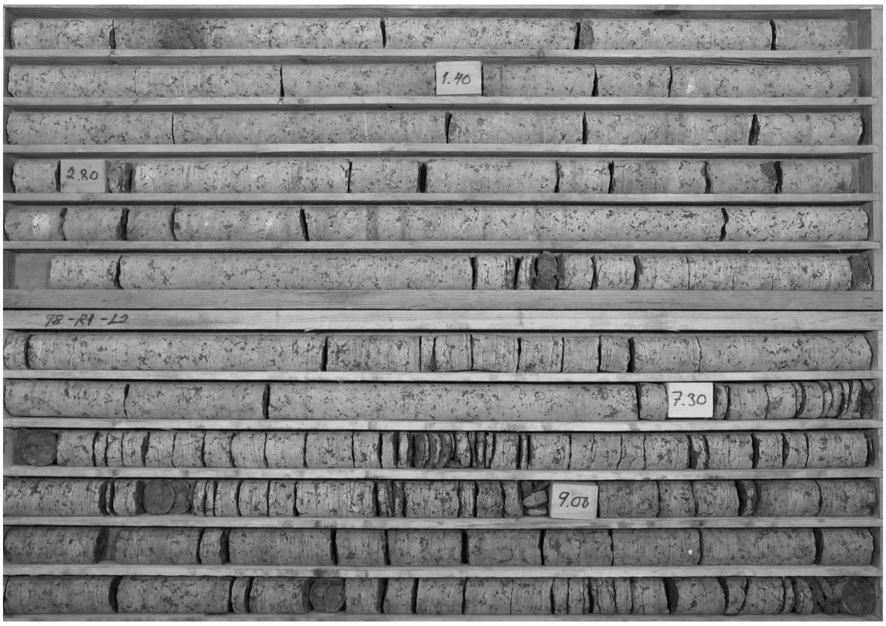


Fig. 5. Drill cores with wiborgite rapakivi granite. Wiborgite from a depth of 7.30 to 11.50 m is heavily weathered, showing intensive subhorizontal fracturing.

in diameter. The matrix is medium-grained. In this rock type the megacrysts lack the rim of plagioclase; only occasionally the megacrysts are mantled. Sometimes angular megacrysts are present. Transition of pyterlite to wiborgite and to porphyritic rapakivi granite is observed. Inclusions of even-grained coarse or medium-grained rapakivi granite are found in pyterlite.

The colour of pyterlite is commonly light red, but red, bluish-red, brownish-red or even brown and bluish-brown varieties can be found. Variations in colour occur even on one single outcrop.

The fracture pattern of pyterlite is orthogonal with open and closed fractures (cf. Fig. 4). Occasional diagonal fracturing occurs. Main fractures are often open. On average, the fracturing is sparse, with the at least 2–3 m spacing of horizontal and vertical fractures as observed on outcrops. Pyterlite has a high potential for natural stone.

Weathering of pyterlite

The upper parts of pyterlite outcrops are weathered down to 1–2 m depth with variation in intensity. The outcrops can in places appear to be intact on the horizontal surface, but the vertical section of the same outcrop reveals that the whole outcrop is totally weathered down to a depth of a couple of metres (Fig. 6). The colour of pyterlite on the outcrop is often altered and represents the colour of a weathered rock with pale and rusty colours.

Porphyritic rapakivi granite

Porphyritic rapakivi granite consists of angular K-feldspar megacrysts (1–3 cm) in a medium-grained matrix. The colour of the rock is red, light red or bluish-red. Porphyritic granite is often found as small areas associated with pyterlite and wiborgite. The mineralogical composition of porphyritic granite is the same as that of pyterlite.

The fracture pattern in porphyritic rapakivi granite is orthogonal. Fractures are both open and closed. Main fractures are generally open. The average density of fractures is 2–3 m. A typical feature of the porphyritic rapakivi granite type is the weathering of the upper parts of the outcrops down to 1–2 m depth on average. The colour of the rock on the outcrop surface represents almost always the colour of a weathered rock with light colours. Porphyritic rapakivi granite has a low potential for natural stone due to its restricted occurrence (Fig. 2).

Even-grained rapakivi granite

Even-grained rapakivi granite is texturally quite homogeneous, but contains occasional K-feldspar megacrysts (1–2 cm in diameter) with the plagioclase rim, as well as angular megacrysts. The main minerals are K-feldspar, quartz, plagioclase, and biotite. The colour of granite is in general red. The fracture pattern in even-grained granite is mainly orthogonal, but diagonal patterns occur as well. The spacing of vertical fractures varies between 1 and 3 m. The spacing of horizontal fractures is denser, 0.5–1.5 m. The potential of even-grained rapakivi granite for natural stone is low. Outcrops of even-grained rapakivi granite appear usually almost unweathered.

Other rock types

Other rock types studied include porphyry aplite and gabbro-anorthosite. Porphyry aplite contains occasional, often mantled K-feldspar megacrysts in a fine-grained aplitic matrix. The density of fractures in the porphyry aplite is 1–2 m. Gabbro-anorthosite is a mafic rock type associated with rapakivi granites. It is coarse-grained, grey, black or bluish-black with an ofitic texture, and contains labradorite with iridescent colours used as gemstone (“spectrolite”). Gabbro-anorthosite is very densely fractured. Outcrops of these rock types appear generally unweathered.

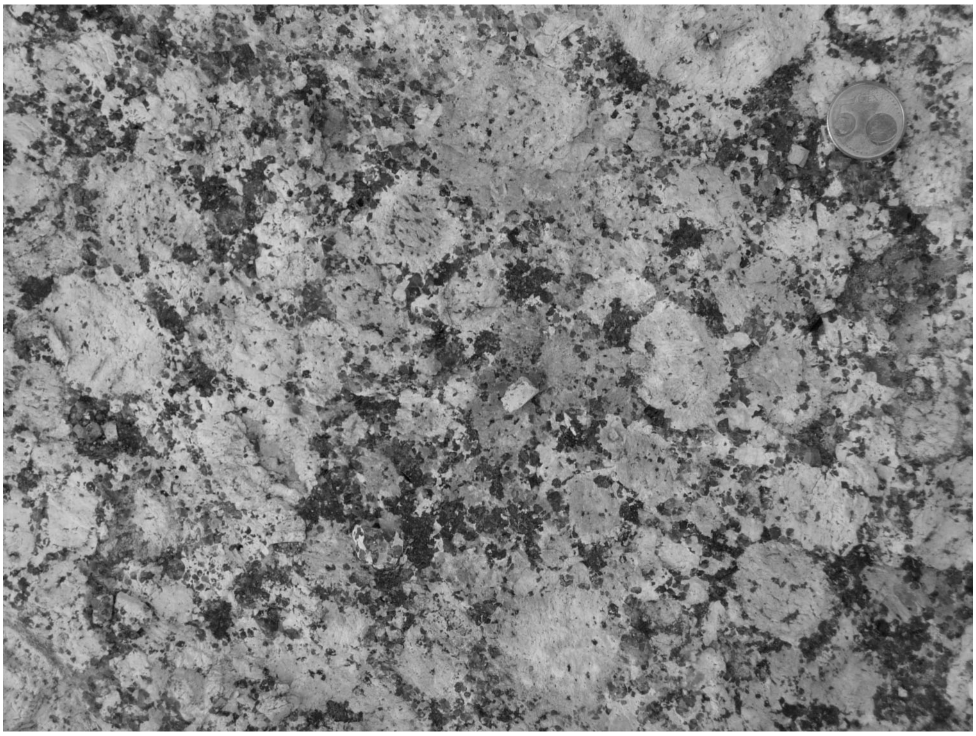
WEATHERING OF RAPAKIVI GRANITE IN SAMPLES AND THIN SECTIONS

Intensive weathering and fracturing can be observed in resin impregnated samples (Fig. 7a) and in thin sections (Fig. 7b). Three generations of microfractures can be discerned.

Two subvertical fracture directions were registered (J1 and J2) (Fig. 8). The J1 fractures are associated with K-feldspar alteration, whereas no alteration was observed in the J2 fractures (Fig. 8). Microfractures with the same subvertical orientations as J1 and J2 in K-feldspar ovoids were also recognized in the field on the same outcrop from where the resin impregnated sample and thin section (Figs 7, 8) were collected. It was established that the J2 direction was dominating over J1. Field measurements revealed no noticeable alteration in fractures in the dominant J2 direction, whereas fractures of the weaker direction (J1) were filled with alteration products, corresponding to the observations on thin sections (Fig. 8).

In rock samples and thin sections the predominant feature is the subhorizontal microfracturing (J3 in Fig. 8), which does not follow any boundaries of mineral grains or ovoids, but cuts straight through the texture of rock in the length of the whole sample. Subhorizontal microfractures traverse K-feldspar ovoids almost straight forwardly; only a small dislocation can be seen when transecting

(a)



(b)

Fig. 6. (a) Subhorizontal surface of a pyterlite outcrop. Diameter of the coin is 2 cm. (b) Subvertical section of the pyterlite outcrop in Fig. 6a shows that rock is totally “grusified”. Length of the hammer is 70 cm.

(a)

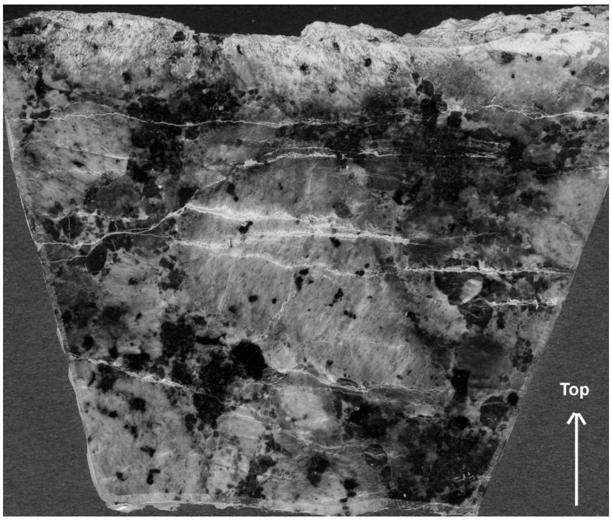
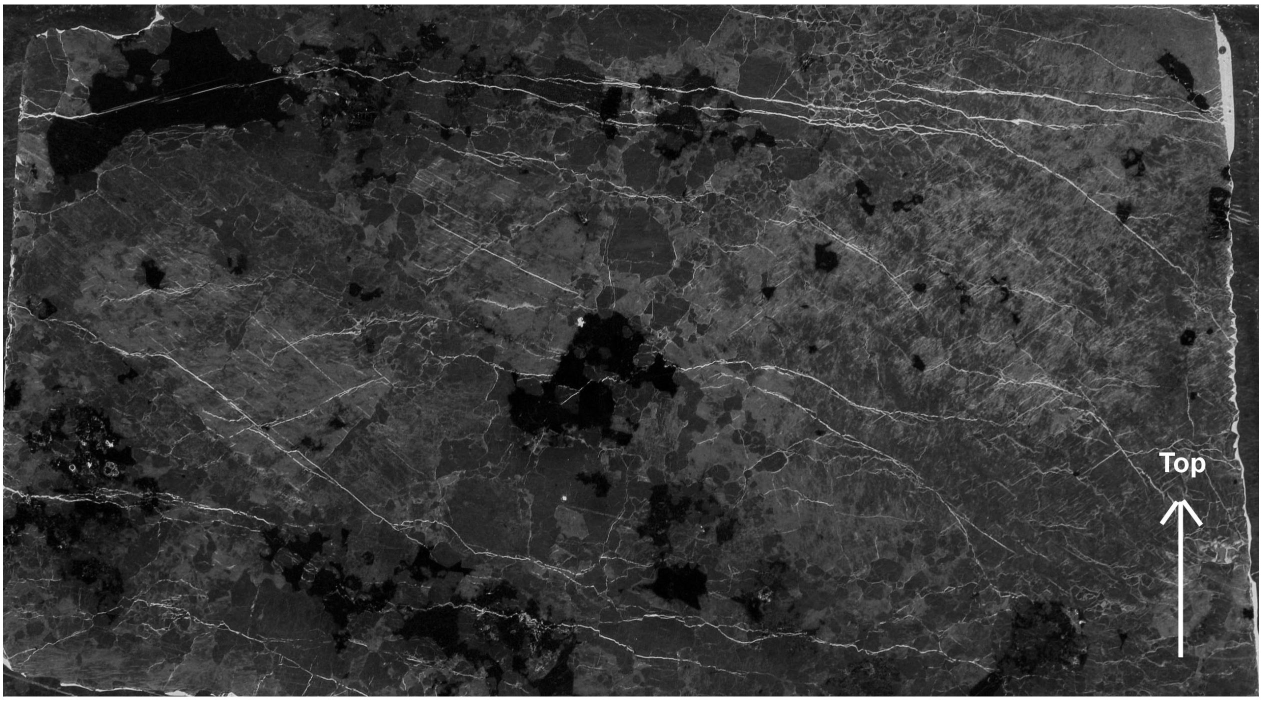


Fig. 7. (a) Subvertical section of a resin impregnated wiborgite rapakivi granite sample taken vertically down from the surface of an outcrop. The upper surface of the sample in the figure corresponds to the upper surface of the natural outcrop. The height of the sample is 5 cm. (b) Thin section from the rock sample in Fig. 7a. Length of the thin section is 3 cm and almost the whole section consists of one single K-feldspar ovoid. Pale stripes represent subhorizontal microfractures filled with fluorescent resin. Photos have been taken in UV-light.

(b)



subvertical microfractures or cleavage plane of K-feldspar (Fig. 8, broken line marked with J3). No alteration products were found in the subhorizontal microfractures in these samples.

Subhorizontal fractures seem to break down the rapakivi granite outcrops and be an essential factor at the beginning of the "grusification" process of the outcrops. The weathering and "grusification" in rapakivi granites begin mechanically along subhorizontal and subvertical fractures. Older fractures have longer time to affect the minerals, hence, the alteration of minerals develops earlier in those directions (along fracture direction J1 in Fig. 8). The fracturing in rapakivi granites is probably a result of intrusion mechanics or subsequent brittle deformation. The tension and stress fields in the intrusion generate subvertical and subhorizontal fractures, and the development of these fractures is connected with the overall tectonic deformation of the bedrock.

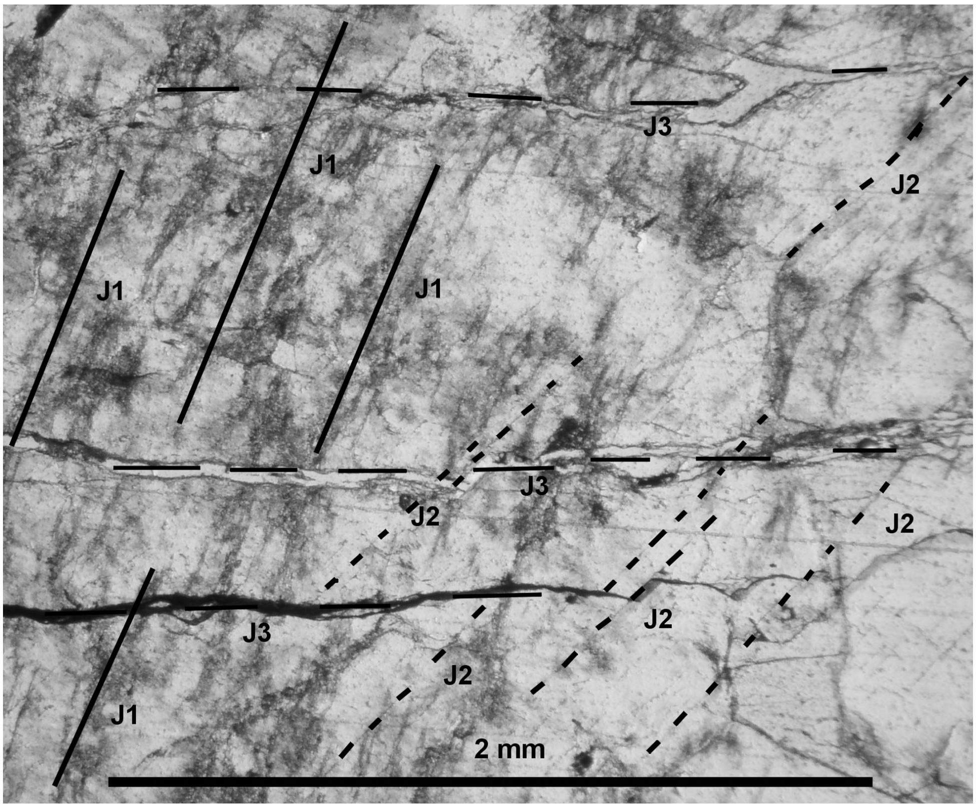


Fig. 8. A closer view of one K-feldspar ovoid in the thin section of Fig. 7b. Pale stripes are fluorescent resin in subhorizontal microfractures (broken line marked with J3). Dark stripes from the top of the photo towards the lower left corner are subvertical microfractures (continuous line marked with J1). Very thin stripes in the right corner of the photo are other subvertical or inclined microfractures (broken line marked with J2).

After the mechanical impact, rapakivi granites begin to weather chemically with the alteration of minerals towards the weathering processes, which could be both mechanical and chemical. The endogene alteration of K-feldspar is the early stage of weathering followed by exogene weathering processes. This is the first step towards the weathering of rapakivi granites but, however, does not explain the random "grusification" of rapakivi granites observed on outcrops.

DISCUSSION

Homogeneous colour and appearance as well as sufficient soundness are among the most important criteria for good quality natural stone, and precise determination of these parameters is essential in the evaluation of natural stone. During this study it was difficult to define the real rock colour at the outcrop surface because of the surficial weathering and staining. On the other hand, weathering did not influence the determination of the texture of the rock; in fact, weathering enhanced the structural form of the rapakivi granite in many cases.

Definition of the macroscopic soundness was not significantly compromised because of the generally wide-spaced orthogonal fracturing in rapakivi granite and because of the minor impact of weathering on the shape of the fractures. In contrast, the microscopic soundness could be defined only by a proper sampling.

During a standard exploration process the colour and soundness are visually evaluated on the outcrop surface, and often the decision on further assessment or even production is based on this surficial evaluation. In common cases this could be justified. However, in rapakivi granite areas the explorer cannot solely rely upon the observations made on the outcrop surface due to weathering. Our observations indicate that weathering can affect the outcrop surface on average down to 1–2 m depth, and occasional subvertical and subhorizontal weathered zones of rock can occur deeper in outcrops. As seen in the samples and thin sections, the structure of the rock is loosened in the weathered zones. The colour varies, e.g. in wiborgite, where it changes irregularly from brown to reddish-brown on the outcrop surface. Colour variations can mainly be attributed to weathering as they were also seen in the upper parts of the drill cores. Our study also shows that even if the macroscopic fracturing would be sparse enough for production, we cannot be sure, only on the basis of outcrop observation, that the rock confined by macroscopic fractures would be intact. In particular regions, in the study area, even up to 80% of the outcrops with coarse-grained rapakivi types can be weathered, which has a significant impact on the exploration and assessment of natural stone. This implies a need for the use of subsurface evaluation methods, especially in heavily weathered areas.

We have used shallow sampling with a hand-held saw, GPR, and core drilling as subsurface methods for studying the rock properties beneath the outcrop surface. These methods are commonly used in natural stone evaluation, and usually the quality of stone can be adequately assessed. In the study area shallow sampling was not a successful method for the determination of the subsurface properties – neither the real colour of the rock nor the soundness could be recognized because the effects of weathering often extend below the 5–10 cm deep sampling.

During detailed investigations, the subsurface fracturing was examined with the GPR along cleaned traverses (like the one in Fig. 3) directly on the bare rock surface, using the antenna of 200 MHz. Distinct subsurface horizontal or subhorizontal fractures could be defined with GPR. In general, GPR is a suitable method for studying the overall soundness of rapakivi granites, because they have a homogeneous structure with no ductile deformation and, consequently, major subhorizontal fractures are easily detectable (see also Luodes 2007a, b). But the resolution of GPR with the commonly used 200 MHz antenna was not high enough to detect the loosened and weathered structure of rock in the surface parts of the rapakivi outcrops. With high-resolution antennae of e.g. 1000 MHz it might be possible to detect the weathered upper zone, but in that case the success of GPR heavily depends on favourable dielectric properties of the rock.

Core drilling was of invaluable help in definition of both the colour and the soundness of rapakivi granite. By the core drilling, we were able to penetrate through the weathered zone and from the core samples the depth of weathering could be exactly determined.

As the core drilling produces actual rock samples in which the colour and the soundness can be studied, it is a very beneficial method in natural stone investigations, but at the same time the most expensive one. A challenge with the core drilling is also that a natural stone prospect or a deposit cannot be drilled as densely as, e.g., an ore body because the drill holes can spoil an otherwise good stone. In standard exploration a mini-drill can be used for the sampling of 15–25 cm long cores with a diameter of 2.5–4.0 cm. This depth of vertical penetration is mostly sufficient for getting unweathered samples, but as shown by this study, it is not always enough in the rapakivi areas. This calls for the development of cheap and light drilling equipment for shallow core sampling. The drill should be easy to move and operate, preferably by one person. Depth penetration should be 5–10 m, i.e. approximately the height of the first production layer.

Because a natural stone occurrence cannot be densely drilled, alternative and non-destructive methods for studying the weathering of rock are needed. Besides GPR, our project has test used some other geophysical methods in the evaluation of natural stone prospects, including magnetic, electromagnetic VLF-R and EM31, seismic, and microgravimetrical methods (Elo 2006; Lanne 2007; Vartiainen et al. 2007). For other solutions to study weathering, see, e.g., Ceryan et al. (2008).

It seems that while some of the methods used by us can be applied to the assessment of the macroscopic fracturing of rock (especially in defining fracture zones), the evaluation of microfracturing and weathering is a more challenging task. However, with the use of the microgravimetrical method knowledge of the thickness of the weathered upper part of an outcrop can be gained. The microgravimetrical study includes accurate gravity measurements along profiles, calculation of standard Bouguer anomaly, calculation of regional terrain correction, modelling the local features of the measurement site, and analysis of the measurements (Elo 2006). The site should be free from overburden. Furthermore, accurate GPS equipment capable of determining the vertical and horizontal coordinates within ±0.02 m should be used. In our case also the distribution of the outcrop surface weathering was mapped in detail. The measured residual gravity minimum coincided relatively well with the mapped outcrop weathering, indicating usefulness of the method. The results can still be improved, e.g. with more detailed modelling of the local characteristics of the measurement site (topographical features, etc.) and more precise knowledge of the density contrast between the weathered and unweathered rock.

We find the subsurface methods used in natural stone evaluation insufficient in weathered rapakivi granite areas. Common core drilling gives good results, but it is expensive and cannot be used in dense sampling. Of the non-destructive geophysical methods, the microgravimetrical one is the most promising for defining the dimension of the weathered zone. In some cases also high-resolution GPR can be used. These methods are not yet complete as standard subsurface exploring methods for natural stone, and further testing is needed until they can be ordinarily used in evaluation.

CONCLUSIONS

The upper parts of the wiborgitic, pyterlitic, and porphyritic rapakivi granite outcrops are affected by weathering of varying intensity. Weathering can reach down to 1–2 m depth and can also occur as random subhorizontal and subvertical zones deeper down in the rock. Weathering changes both the colour and soundness of rapakivi granite. Subsurface quality assessment methods, by which the dimension of the weathered upper part of the outcrop can be defined, should always be used in rapakivi granite areas. Development of subsurface methods is needed, so that they would be better suited for the assessment of natural stone in weathered terrains.

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Rabakivi graniidi paljandite pindmise murenemise tähendus loodusliku kivi uuringutel ja kvaliteedi hindamisel

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Rabakivi graniidi pindmise murenemise tähendust loodusliku kivi hindamisel uuriti Soome kaguosas Viiburi rabakivi batoliidi paljandites. Uuring toimus kogu batoliiti hõlmava kaardistamisena ja valitud paljandite detailse uurimisena. Viiburi batoliidis määrati järgmised erimid: viiburgiit, piiterliit, ühtlaseteraline rabakivi, porfüürne rabakivi, porfüürilaadne apliit ja gabro-anortosiit. Neist kõige levinum on esimene ja kergemini alluvad murenemisele jämedateralised erimid, nagu viiburgiit, piiterliit ning porfüürne rabakivi. Murenemine on enamasti pindmine, erineva intensiivsusega, ulatudes kohati mööda lõhesid ka sügavamale. Murenenud kivimi värvus on muutunud ja kivimi omadused halvenenud, mis on olulised kivimi väärtuse hindamisel. Peetakse vajalikuks luua meetodid, mis võimaldaksid eristada murenenud kivimit massiivi sees olevast hea kvaliteediga kivimist.