National treasure of global significance. Dimension-stone deposits in larvikite, Oslo igneous province, Norway

Tom Heldal[1], Idunn Kjølle[2], Gurli B. Meyer[1] and Sven Dahlgren[3]

[1]Geological Survey of Norway (NGU), 7491 Trondheim, Norway.
[2]Directorate of mining, 7491 Trondheim, Norway.
[3]Geological advisor, Buskerud, Telemark and Vestfold, Fylkeshuset, 3126 Tønsberg, Norway.
E-mail: tom.heldal@ngu.no

Larvikite has for more than a hundred years been appreciated as one of the world's most attractive dimension stones, and at present, its production and use is more extensive than ever. The main reason for the continuous success of larvikite on the world market is the blue iridescence displayed on polished surfaces, which is caused by optical interference in microscopic lamellae within the ternary feldspars. The larvikite complex consists of different intrusions, defining several ring-shaped structures, emplaced during a period of approximately five million years. Following this pattern, several commercial subtypes of larvikite, characterised by their colour and iridescence, have been mapped. Four of these subtypes are being exploited at the present time and define the most important reserves in the short run. Some other subtypes are less attractive in the present market situation, but may provide an interesting potential for the future. However, the industrial value of the larvikite also depends on other geological features, such as various types of dykes, faults and fractures, ductile deformation zones, late-stage magmatic and hydrothermal alteration and deep weathering. When combining the distribution pattern of such features with the map of the larvikite subtypes, it is possible to delineate various types of larvikite deposit that are considered to have commercial value in the short or long term. Finally, reserve estimates for the different types have been made, showing that some of the most attractive types have rather limited known reserves if the present level of production is maintained or increased.

Heldal, T., Kjølle, I., Meyer, G.B. and Dahlgren, S. (2008) National treasure of global significance. Dimension-stone deposits in larvikite, Oslo igneous province, Norway. *In* Slagstad, T. (ed.) *Geology for Society*, Geological Survey of Norway Special Publication, **11**, pp. 5–18.

Introduction

The name 'laurvikite' was first applied by Waldemar Brøgger in his descriptions of the monzonitic rocks within the southern part of the Carboniferous–Permian Oslo igneous province (Brøgger 1890, see also Dons 1978) (Figure 1). The rock name

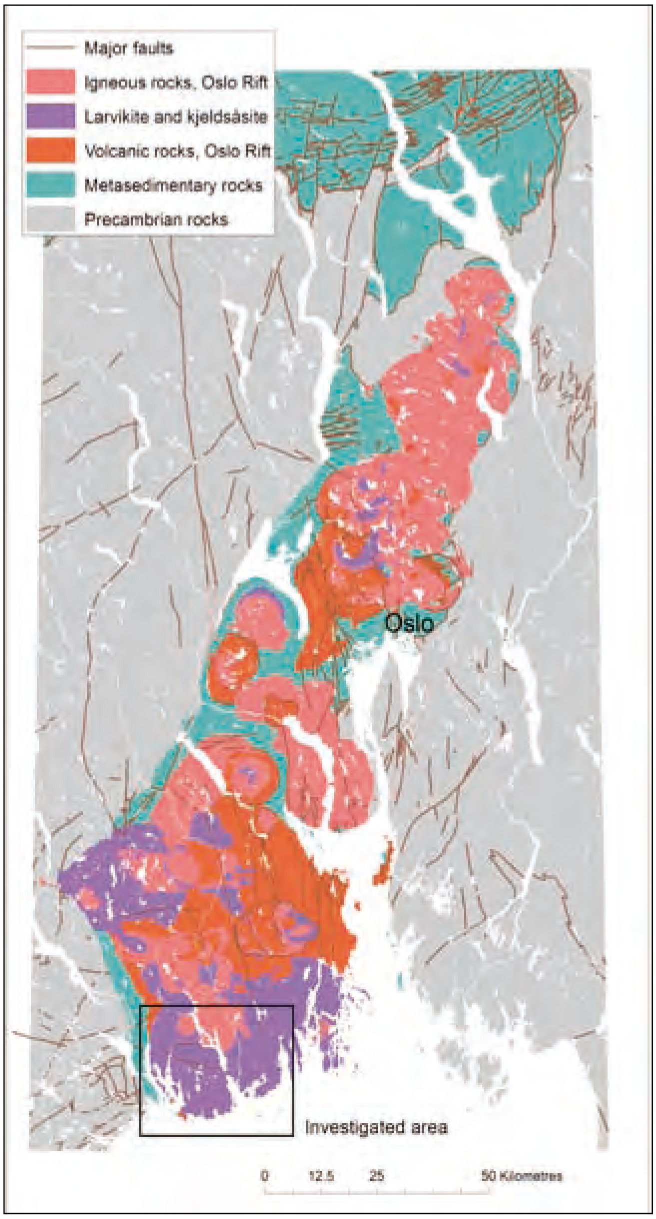


Figure 1. Overview of the Oslo Rift and distribution of larvikite and similar rocks. Modified from NGU digital maps of the Oslo region.

was later changed to 'larvikite' having its origin in the small coastal town of Larvik (Laurvik in Brøgger's days), situated almost right in the centre of the main larvikite plutonic complex. The larvikites form a series of semi-circular intrusions, varying from quartz-bearing monzonite in the east (earliest phases) towards nepheline-bearing monzonite and nepheline syenite in the west (latest phases, Figure 2). From a geologist's point of view, the larvikites are important for understanding the tectono-magmatic processes responsible for the formation of the Oslo Rift. However, most other people see larvikite as a particularly beautiful rock. The reason for this is the abundance of ternary feldspar displaying bluish to silvery play of colours or iridescence. This aesthetic uniqueness has caused larvikite to become one of the world's most used and appreciated dimension stones, cladding hundreds of prestigious buildings and thousands of kitchen tops world-wide, and lately also the nomination and approval of larvikite as the 'National rock' of Norway (Heldal 2008). Production started already in the 1880s, and at present, the export value of rough blocks of dimension stone from the Larvik region lies between a half and one billion NOK, distributed on approximately 30 individual quarries (Figures 3 and 4). Different types of larvikite have different market value, and the customers can choose between a range of types and qualities under trade names such as 'Blue Pearl', 'Emerald Pearl', 'Royal Blue' and 'Marina Pearl'.

This paper presents the results of a more or less continuous, ten-year project aimed at mapping and characterising the most important larvikite deposits, in order to identify and delineate deposits that can be of industrial importance in the short and long run. Being located in an area with an increasing population, the larvikite deposits are certainly under pressure from other land-use interests, and thus the needs of documenting and securing future deposits are indeed urgent.

Geology and previous research

Larvikite and associated plutonic rocks compose a significant part of the bedrock within the Carboniferous–Permian Oslo Rift, predominantly in its southern part (Figure 1). Although dimension-stone quarrying has been carried out in many places, it is first of all in the vicinity of Larvik town that exploitation

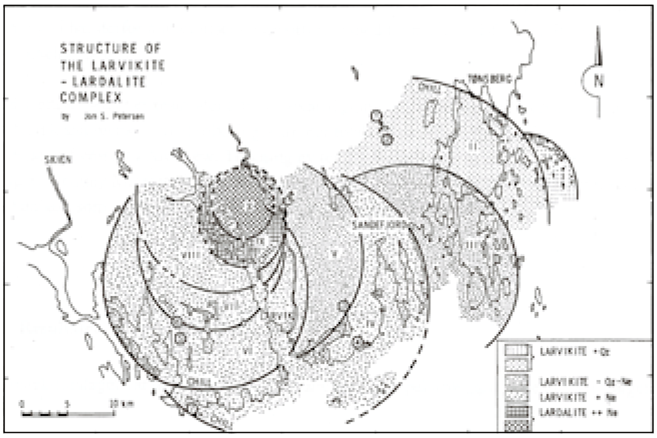


Figure 2. The larvikite ring complex as interpreted by Petersen (1978a). Map from Oftedahl and Petersen (1978).

Figure 3. Larvikite quarry at Klåstad (Emerald Pearl).

Figure 4. Stock of larvikite blocks at Tvedalen ready for shipping abroad.

has developed to a permanent and sizeable industrial activity, and which has been the target area for the present study (Figure 1).

After Brøgger's (1890) pioneering work on the igneous rocks of the Oslo Rift, little research on the larvikites, with the exception of mineralogical investigations mentioned above, was carried out until the 1970s. Petersen (1978a, b) was the first to suggest that the larvikite complex is composed of several, ring-shaped intrusions, younging from east to west. He suggested 8 such ring fragments (numbered I to VIII), based on topographic features, magnetic anomalies and field observations of some of the contact zones (chilled margins, Figure 2). Furthermore, Petersen (1978a, b) observed a systematic change in the mineralogy from quartz-bearing larvikite in the east towards nepheline-bearing larvikite to the west, approaching the lardalite and nepheline syenites in the 'centre' of the plutonic complex. This led Petersen (1978a, b) to suggest a sequential evolution from saturated to undersaturated magma fluxes. This could result from either multiple caldera collapses or a system of multiple ring intrusions from a deep-seated parental magma chamber (Neumann et al. 1977, 1988, Neumann 1978a, 1980, Petersen 1978a, b).

Neumann (1980) confirmed Petersen's model of the separate ring intrusions through geochemical analyses, and also showed geochemical evolution patterns within each ring intrusion. Neumann furthermore provided geochemical evidence that the larvikites are the plutonic equivalents to the overlying, once massive sequences of romb porphyry lava flows exposed in the surrounding areas (Neumann 1978b). Dahlgren et al. (1998) confirmed the progressive evolution of the ring intrusions through time by U–Pb dating, giving a range of ages between 297 ± 1.2 Ma (eastern larvikite) and 293.2 ± 1.3 Ma (western larvikite). Nepheline syenite, being the youngest intrusion in the sequence, was dated at 292 ± 0.8 Ma. More recently, Larsen and Olaussen (2005) devised a model for the evolution of the Oslo Rift, where the larvikite/romb porphyry lavas define an intermediate step in the rift formation, i.e., in-between the early volcanism (basalt fissure eruptions and plateau basalts) and later caldera formation.

The first record of larvikite as a source for dimension stone is a letter dated October 1811, from a certain Ohlsen to 'Headmaster Floor', where the former suggests extraction of larvikite, among other purposes, for a castle in Copenhagen (referred to in Oxaal 1916). However, nothing happened until 1884, when quarrying was initiated by Ferdinand Narvesen close to the town of Stavern, southwest of Larvik. A few years later, Theodor Kjerulf, then director of the Geological Survey of Norway (NGU), took part in the further development of the industry by recommending the deposits of dark larvikite southeast of Larvik. Oxaal (1916) did the first survey of the quarried larvikites and described the quarrying activity in the area. Reid Kvien, a geological consultant in Larvik, was the first to apply Petersen's model in his interpretation of commercial larvikite types and in compiling the first resource map for the municipality. In recent years, NGU has carried out surveys of the larvikite deposits (Heldal et al. 1999, Kjølle et al. 2003), on which this paper is based.

Larvikite is generally a coarse-grained plutonic rock consisting of tabular to prismatic crystals of ternary alkali feldspar (10–50 mm) intergrown with interstitial stubby to ragged prisms (2–5 mm) or 10–50 mm oikocrysts of augite (diopside-augite in the larvikites used for dimension stone) and/or hornblende (calcic amphiboles), interstitial grains of Fe-Ti-oxides and biotite in addition to oikocrysts or subhedral rounded grains of olivine (Fo_{25-55} in the larvikites used for dimension stone). Quartz occurs interstitially in the larvikites of the eastern part of the area while nepheline takes over for quartz in the central to northwestern part (Figure 2). Nepheline occurs both as interstitial grains and as subgrains and intergrowths in the ternary feldspars. Apatite is a minor phase forming inclusions in particular in olivine and Fe-Ti-oxides. Micro inclusions of zircon, titanite and complex Nb-Th-REE-minerals occur in all the above-mentioned mineral phases. The larvikites are generally composed of 80–95% feldspar, 1–5% Ca-rich pyroxene, 1–5% amphibole, 0–5% olivine, 1–5% Fe-Ti-oxides, ~1% apatite, 1–5% biotite, ± 1–5% nepheline, ± 1–5% quartz and the accessory minerals zircon, baddeleyite (ZrO_2) and sphene. The bulk of the feldspar is ternary (Barth 1945), with compositions in the range $An_{4–30}Ab_{58–82}Or_{3–35}$ (Oftedahl 1948, Muir and Smith 1956, Smith and Muir 1958, Rosenqvist 1965, Nielsen 2007). In the larvikite types used for dimension stone, the ternary feldspar is composed of flame-like to patchy intergrowths of various phases of feldspar. Individual flames and patches range in 'bulk' composition from alkalifeldspar compositions close to sanidine, towards albite and/or anorthoclase and/or pure plagioclase compositions. Flames and patches with iridescence are composed of microscopic to submicroscopic lamellae of two phases of feldspar. A common feature of the feldspars is the occurrence of partly resorbed grains of plagioclase (oligoclase) in addition to subgrains and intergrowths with nepheline (Nielsen 2007).

The feldspars in the larvikites have bulk compositions containing significant proportions (> 5%) of Ab, Or and An. Feldspar of this composition is sometimes referred to as mesoperthite, but here we prefer the more general term ternary feldspar. As pointed out by Ribbe (1975), this composition causes instability in the crystallographic structure and leads to exsolution similar to that in alkalifeldspar. The bright optical interference colours (iridescence) seen in certain varieties of larvikite are due to optical refraction in the exsolution pattern of alternating orthoclase and anorthite ($An_{15–18}$) lamellae. The intensity as well as the colour of the iridescence depends on the spacing and geometry of the lamellae, and iridescence generally occurs when the thickness of lamellae is in the range 500–1000 Å (Figures 5 and 6).

Another kind of variation is in the distribution of iridescence within single feldspar crystals and three main groups can be defined: patchy (irregular patches within each crystal), homogenous (within a crystal) and zoned (see Figure 7). Partly, we can see a tendency where the younger larvikites (such as the Blue Pearl subtype) contain predominantly patchy iridescence patterns, while some of the older (such as the Emerald Pearl subtype) more commonly have homogeneous or zoned iridescent crystals.

Quarrying larvikite — aspects of industrial quality

Larvikite is extracted in rectangular blocks aimed for export markets. To obtain the highest market value, the blocks must be large (preferably larger than 4 m^3) and homogeneous. If the blocks contain flaws, veins, discolouration or other features reducing the uniformity of colour and quality, the market price for the blocks is reduced significantly, if they can be sold at all. The average block yield in the larvikite quarries is close to 10%, which means that nine out of ten cubic metres of extracted rock are not utilised as dimension stone. However, the leftover rock from dimension-stone quarrying is to an increasing extent used for other purposes. Large 'waste' blocks are shipped to the UK and other North European countries to be used for coastal protection, and some of it is crushed to rock aggregate. The rest is deposited in designated landfill areas close to the quarries.

In general, the surveys that have been carried out in the larvikite areas have focused on the main geological aspects of importance to the industrial demands, basically the fundamental success factors for the quarries.

Attractive and uniform colour is the most important issue besides the block size. In general, larvikite displaying strong blue play of colours (iridescence) is more attractive and valued than larvikite with weaker blue and/or silvery colour play (Figure 5). The variation in colour essentially follows the ring pattern identified by Petersen (1978a), i.e., related to the individual intrusive phases.

Discolouration of the larvikite is assigned to late- to post-magmatic alteration of the larvikite, varying from 'bleach-

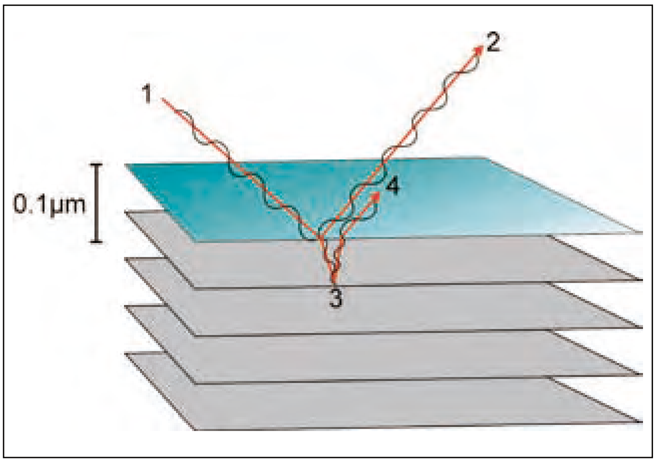


Figure 5. Principle of how iridescence forms in a media, such as feldspar crystals. The reflected light beam (1–2) and the refracted beam (1–3–4) reinforce each other because their phase difference is an integral number of wavelengths. Other wavelengths present in a beam incident at this angle will interfere, resulting in the optical interference colours.

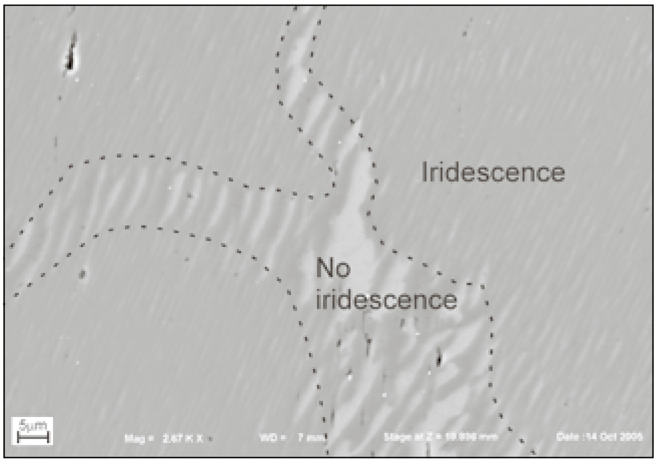


Figure 6. Scanning electron microscope photo of exsolution lamellae in larvikite. Iridescence occurs when the spacing of the lamellae is from 500 to 1000 Å (marginal parts of the photo).

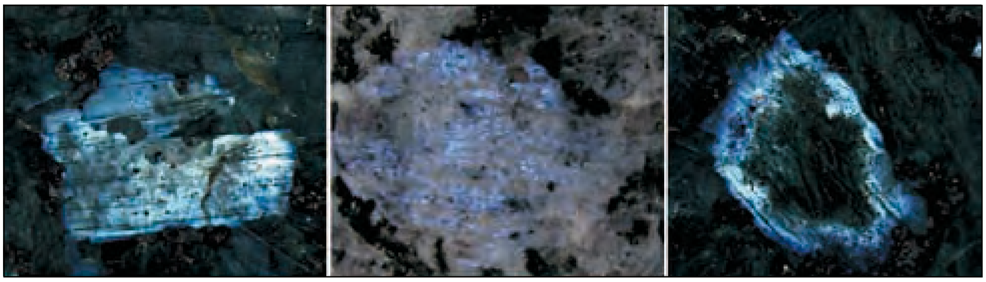


Figure 7. Types of iridescence in feldspar. Left: homogenous. Centre: patchy. Right: zoned. Each photo measures 2 cm horizontally.

ing' (sericitisation) to 'rust' (oxidation of ferrous minerals). Discolouration may be of local importance within a single quarry, or more pervasive, influencing larger bodies of larvikite. In general, all discoloured larvikite is discarded as waste rock. Similarly, dykes of basalt and romb porphyry, as well as pegmatite, make large volumes of larvikite undesirable for quarrying.

The spacing of joints and fractures determines the block size, and is thus of great importance. This feature is controlled by the physical properties of the larvikite and structures such as fault systems. In parts of the area, ductile shear zones in the larvikite similarly reduce the block potential. Moreover, modal layering and planar alignment of the feldspars ('cleavage'[1] and planes showing iridescence) are important for establishing quarrying and sawing directions of the rocks.

Methodology in the investigation of larvikite

In addressing the aspects of industrial quality as shown above, we have chosen to focus the investigations along several avenues of research. Firstly, it has been necessary to establish appropriate methods for characterising unique commercial types of larvikite in the field, without carrying out costly and time-consuming investigations such as core drilling. Polished samples of both weathered and non-weathered rocks were used as reference for evaluating the visual appearance of the iridescence colour on hand specimens (colours and intensity). The regional distribution of such types was then mapped. Secondly, the regional pattern of alteration (discolouration) was evaluated, aiming to exclude areas where such features bear a strong and penetrative impact on the quality. Thirdly, the relationship between structures (faults, fracture zones and fabric), topographic features and block-size potential was investigated. Finally, by combining these data sets, we have delineated deposits of different quality according to their market value and to their short- and long-term exploitation potential. This has, furthermore, enabled us to calculate reserves and deliver a model for management of the larvikite resources in the area.

In addition to geological mapping in the field, airborne geophysical surveys carried out in the late 1990s (Mogaard 1998, Beard 1999) proved to be of great value for the regional interpretation, particularly in revealing the overall structural pattern of the larvikite complex. Digital terrain models equally proved helpful in the interpretation of fractures and joint systems.

Defining and mapping commercial larvikite types

Colour, iridescence and subtypes

For field classification of larvikite, a simple characterisation of iridescence intensity and colour (blue, light blue, silvery) proved applicable to both hand specimens and for the interpretation of commercial types of larvikite.

In addition to the iridescence, the larvikite subtypes vary in overall 'background' colour, from dark grey (almost black) to light grey, and there are also systematic variations in maximum grain size (mostly from 1 to 6 cm) and grain-size distributions. Variations may also be seen in the degree of alignment of the feldspar crystals and modal layering. Combined with the interference colours, these latter features largely define the commercial and unique subtypes of larvikite, which can be mapped in the field. Other geological aspects, such as mineral content (mode), show too small variations within the area to be of any significant help in the field survey.

In Table 1, larvikite subtypes are defined on the base of colour and texture. The most important ones are shown in Figure 8. Most of the subtypes have been given names from typical quarry areas.

Geophysical data

In addition to field surveys based on the criteria given in Table 1, airborne geophysical surveys (Mogaard 1998, Beard 1999) have proven to be of great value in the interpretation of larvikite-subtype distribution. The magnetic map (Figure 9) by far confirms the pattern of ring-shaped intrusions established by Petersen (1978a, Figure 2), although not along exactly the same lines as he proposed. In addition, the map gives us new information about faulting of the larvikites. In particular, two large faults are recognised, hereafter named the Farrisvann fault (in the east) and the Langangen fault (in the west). These two faults follow the general pattern of the Oslo Graben and the structures

[1] Cleavage is a practical term used in the stone industry describing splitting directions of rocks, generally coinciding with mineral fabric.

Table 1. Characteristics of different subtypes of larvikite.

Subtype	Iridescence intensity			Iridescence colour			Mineral orientation		Background colour			Max grain size		
	Very weak/ absent	Medium	Strong	Blue	Silver/ bronze + blue	Silver/ bronze	Strong	Weak	Dark grey	Medium grey	Light grey	Small	Medium	Large
Kjerringvik	X	X			X		X				X		X	
Bergan		X		X			X		X			X		
Klåstad			X	X				X	X					X
Stålaker			X	X				X		X	X			X
Eastern Larvik		X				X		X		X	X			X
Larvik zone		X			X			X		X	X			X
Tvedal			X	X			X			X			X	
Bassebu-Prestskjegg	X	X			X		X			X	X		X	
Malerød			X	X			X				X			X
West thin zones			X	X			X			X			X	
Northern zone			X	X			X		X				X	
North zone	X						X				X	X		

divide the larvikite complex into three blocks, which seem to have different potential for natural stone deposits.

Although the internal structure of the larvikite complex is evident on the magnetic map, its northern borders are not clearly defined (transition to lardalite, and a circular intrusion of alkali syenite northwest of Farrisvann). However, on the thorium anomaly map (Figure 10), these two features are clearly seen, while the internal variations are more diffuse.

If we compare Petersen's (1978a) outline of the ring structures with the ones appearing on the magnetic anomaly map, there is a rough fit between the two. However, it seems that the structural complexity of the larvikite massif is higher than the simplified outline of the individual ring intrusions applied by Petersen (1978a). For example, the contact between ring IV and V in the eastern part of the area cannot be traced geochemically (Nielsen 2007). In contrast, Nielsen's geochemical profile suggests an intrusive contact slightly towards the southeast, coinciding with the anomaly pattern as seen in the easternmost part of Figure 9. To the west and northwest of Stavern, there are several thorium and magnetic anomalies that are difficult to explain from Petersen's (1978a) model, none of them actually plotting on the assumed contact of ring IV and VI. As the bedrock in the area is heavily covered by soil, it is difficult to confirm and interpret these structures in the field. However, it is likely that they represent a combination of igneous and tectonic features.

Distribution of unique larvikite types

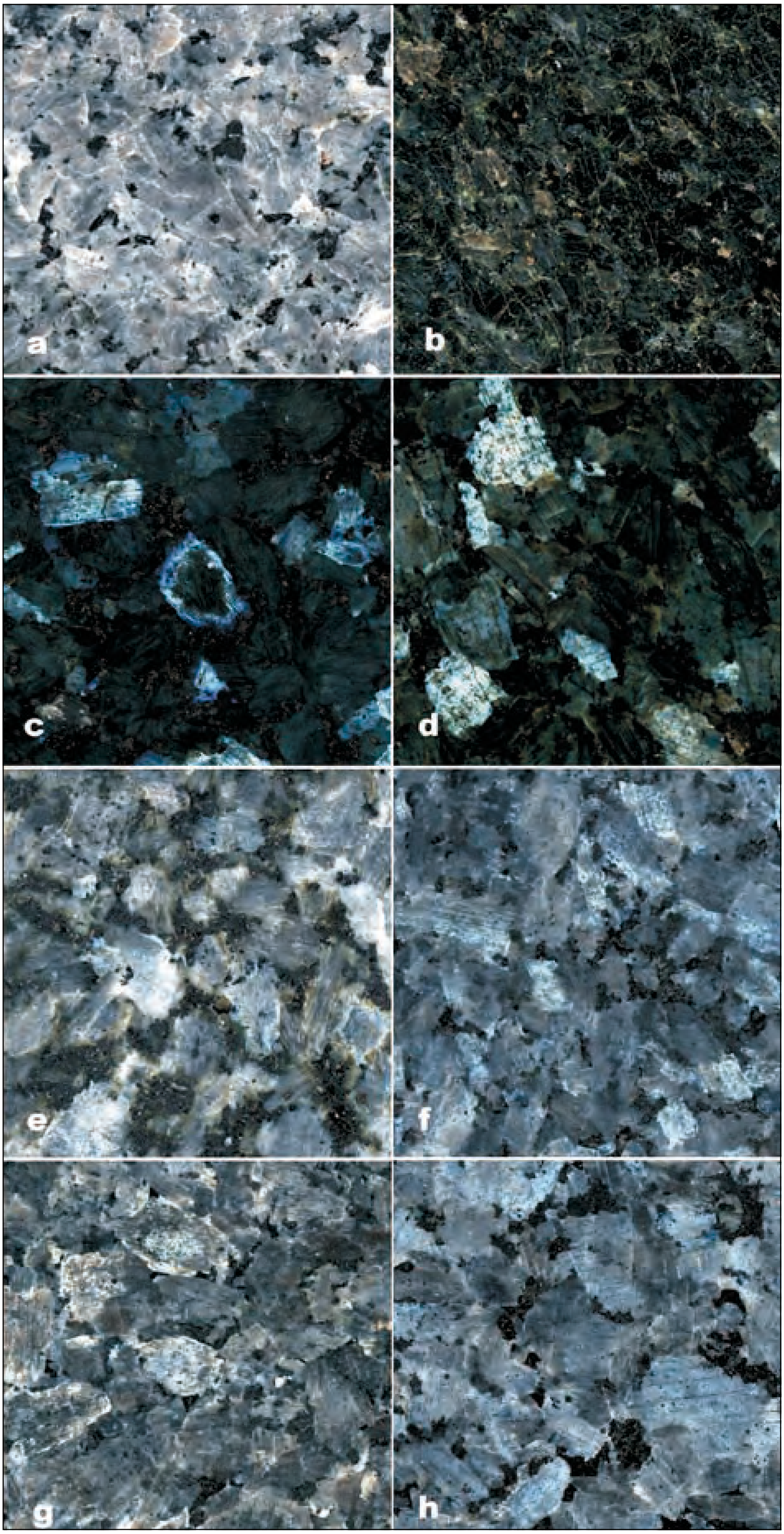
With the geophysical data in mind, mapping of larvikite subtypes was carried out. The survey confirmed that there are complex variations of larvikite, even within each subtype, particularly in the southern and eastern part of the area. Thus, the subtype map in Figure 11 (see also Table 1 and Figure 8) displays the regional variations, not taking into account the very fine-scaled differences. From east towards northwest, the subtypes can be described as follows:

The *Kjerringvik* subtype defines most of the area named ring IV by Petersen (1978a). It consists of quite homogenous, light grey larvikite with weak iridescence. In its eastern part, magmatic layering is commonly seen. There are a few abandoned quarries in this subtype, but it is considered to be of minor importance to future exploitation.

Several thin zones of dark and relatively fine-grained (most grains smaller than 1 cm) larvikite are found along the western margin of the Kjerringvik subtype. These are collectively named the *Bergan* subtype. Blue iridescence can be seen in the feldspars, but it is not the most distinct feature of the rock. Thus, this subtype is the only larvikite in production that predominantly is applied for non-polished workings, such as paving slabs and other outdoor uses.

The *Klåstad* subtype (also called Emerald Pearl) is one of the most attractive larvikite varieties, quarried since the 1880s. It is one of the darkest varieties of larvikite, and iridescence varies from dark blue to silver/bronze, of which the former variety is

Figure 8. Larvikite subtypes, polished slabs 7 x 7 cm. (a) Kjerringvik, (b) Bergan, (c) Klåstad strong blue (Emerald Pearl), (d) Klåstad silvery to light blue, (e) Stålaker (Marina Pearl), (f) Tvedalen (Blue Pearl), (g) Bassebu, (h) Malerød (Royal Blue).



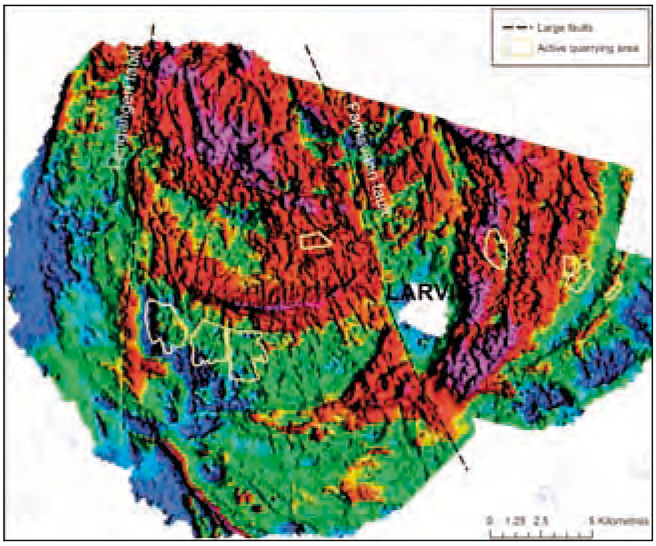


Figure 9. Magnetic anomaly map of the Larvik area, and interpretation of faults.

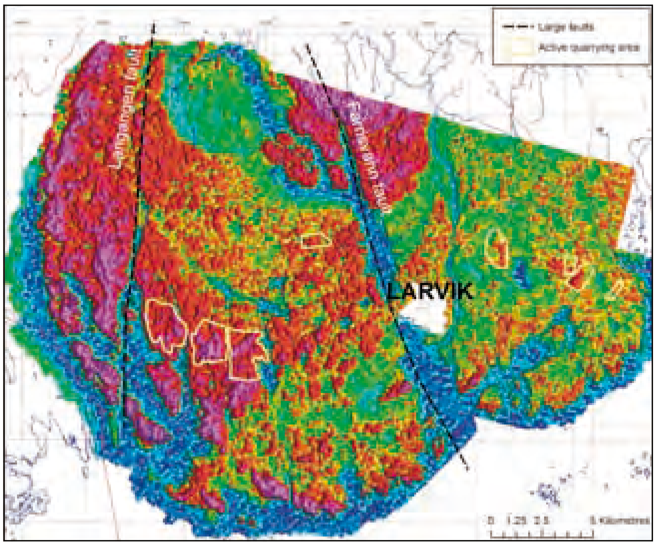


Figure 10. Thorium anomaly map of the Larvik area.

by far the most valuable. There are large, potential reserves of this subtype beneath the farmland between Larvik and Sandefjord, but so far we have little information about the quality.

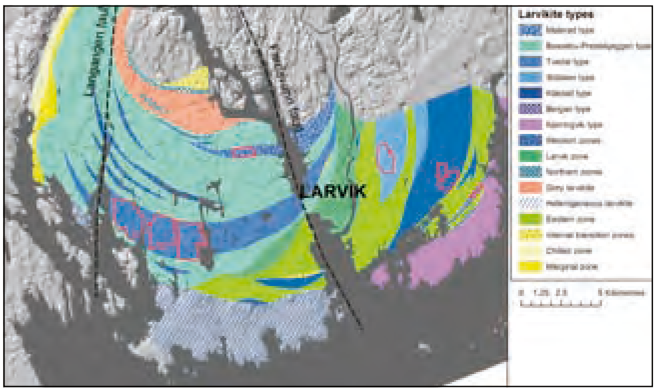


Figure 11. Distribution of unique, commercial subtypes of larvikite.

Minor occurrences, although hardly of commercial value, are found west of Larvik.

The *Stålaker* subtype is light-coloured with bluish iridescence, and has generally a higher content of mafic minerals than other light-coloured subtypes. There are a few large quarries in this subtype, marketed under the commercial name Marina Pearl. A variegated zone of non-commercial larvikite occurs in-between the former subtypes, collectively named the *Eastern Zone* on the map. A zone of *heterogenous larvikite* southwest of Larvik is also difficult to exploit on a modern industrial scale, although it was in this zone that the first quarrying was initiated in the early 1880s.

In addition to the Klåstad subtype, the light-coloured *Tvedalen* subtype (Blue Pearl), displaying strong, blue iridescence, is the best known and at present the larvikite subtype with the highest production rates. Although this subtype can be followed laterally for almost 20 km, only the present quarry areas in Tvedalen and at Auen have proven to contain homogeneous quality in sufficiently large volumes to secure long-term sustainable production. The areas just south of and north of Tvedalen are dominated by light-coloured larvikite with slightly weaker and more silvery iridescence, named the *Bassebu–Prestskjeggen* subtype, of which there might be a future potential for exploitation. Some narrow zones contain larvikite with a stronger bluish iridescence, similar to the Tvedalen type (*Western zones*).

The *Malerød* subtype (commercial name Royal Blue) was introduced commercially as late as in the 1970s, and the area has subsequently become an important production site. It is coarser grained than other light-coloured larvikite types and displays bright blue iridescence. The subtype can be followed both to the east and west of the present production area, and even east of Farrisvann. However, in the latter area, the rocks are more intensively fractured than on the western side, and thus less likely to represent an important resource.

In the far north of the area, most of the outcrops consist of grey larvikite with very weak to non-iridescent feldspar, and thus hardly of any commercial interest. A few narrow bands (*Northern zones*) of dark grey larvikite with strong, dark blue iridescence may represent an exception, but it is uncertain whether these bands are too narrow and too altered for economical production.

A marginal zone and a chilled zone occur along the eastern and northern margins of the larvikite complex, both of no commercial interest. Minor occurrences of similar chilled margins (as described by Petersen 1978a) are also found elsewhere within the complex.

Geological features and their impact on quality

Discolouration

Discolouration of larvikite due to alteration of the minerals is one of the key problems in the quality of the deposits. Not only does discolouration influence the overall colour of the larvikite, but also, and more importantly, effaces the iridescence. The type of alteration that bears most impact on the larvikite quality is 'bleaching' of the feldspar, either locally along cracks (Figure 12) or more penetratively (Figure 13) forming aggregates of different secondary minerals (e.g., zeolites, albite, sericite, analcite, sodalite). Where the alteration is penetrative, the discolouration starts at grain boundaries and continues into the feldspar grains along the mineral cleavage (Figures 13 and 14). Blocks containing bleached larvikite are at best much lower priced than unaltered ones. Although alteration is a common phenomenon in practically all the quarries in the area, and thus contributes to the high waste ratio, it is much more severe and penetrative to the west of the Langangen fault than elsewhere. Therefore, we consider the whole area between the Langangen fjord and the western margin of the larvikite complex to be of no interest for future larvikite exploitation.

Oxidation of larvikite causes development of rusty brown discolouration along joints and fractures. It is a common phenomenon, but predominantly occurs along the major fracture zones. Since such highly fractured areas are of little interest for exploitation anyway, this type of discolouration has minor practical impact on larvikite extraction.

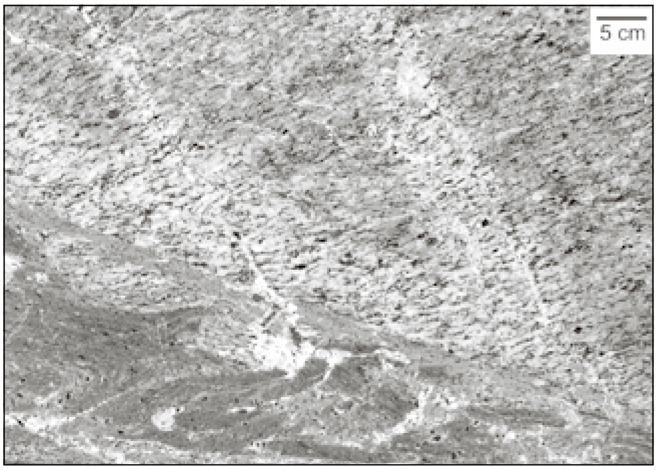


Figure 12. Shear zone along dyke in larvikite, overprinted by fracture-bound alteration (bleaching).

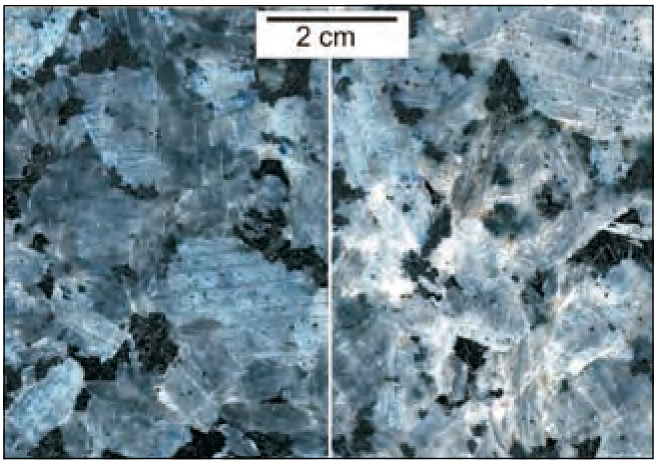


Figure 13. Bleaching of larvikite and impact on aesthetic quality. Unaltered larvikite of the Malerød subtype (left) and altered (right).

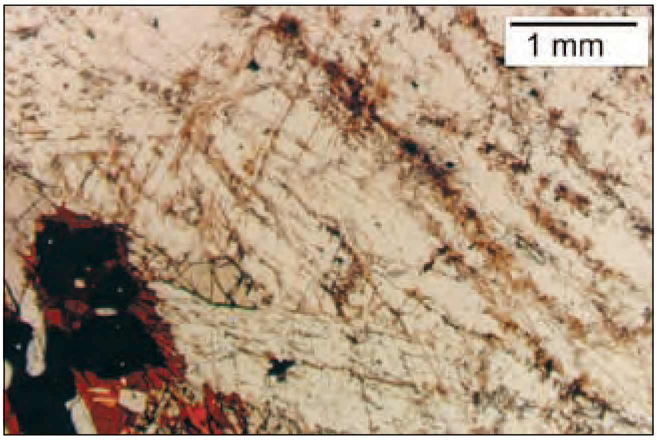


Figure 14. Alteration (brown) in thin section along cleavage planes (plane polarised light).

Joints, fractures and physical properties

In the early history of larvikite quarrying, the occurrence of parallel joints was considered useful—unless the spacing was too small—in facilitating extraction by reducing the need for drilling and blasting. In modern quarrying, however, the sizes of blocks are much larger than in the past, and most of the quarrying is aided by diamond-wire sawing. Thus, the rocks should ideally be as massive as possible. Throughout the years of production, we see clearly how the production areas have moved towards more and more massive larvikite.

The map in Figure 15 presents the regional pattern of fracturing and faulting in the area, based on a lineament analysis of the terrain features. In addition to the two large faults and related structures we see numerous smaller ones, generally having N–S to NW–SE orientation, coinciding with the general fracture pattern in the Oslo Rift. Other strong lineaments follow the planar alignment of the feldspar in the larvikite, and some of these provided the topographic features for Petersen (1978a) in his interpretation of the ring structures. Such features may indeed follow intrusive contacts (Petersen 1978a), but since they are aligned with the main plane of weakness in larvikite there might also be other explanations. Yet another set of fractures appears to be related to the igneous structure of the larvikite. Joints perpendicular to the mineral orientation may represent cooling structures and, in some cases, these are associated with fine-grained larvikite dykes. The magnetic map clearly shows the radiating nature of such structures in and around the Tvedalen area.

The major fracture systems have shaped the topography of the area; the large valleys follow the first-order structures such as the N–S to NW–SE faults and the ring structures (Figure 16). Second-order structures, such as the conjugate NE–SW-trending fractures associated with N–S-trending faults, tend to control the location of smaller valleys. On a more local scale, the pattern is even more complex; each block bordered by first-

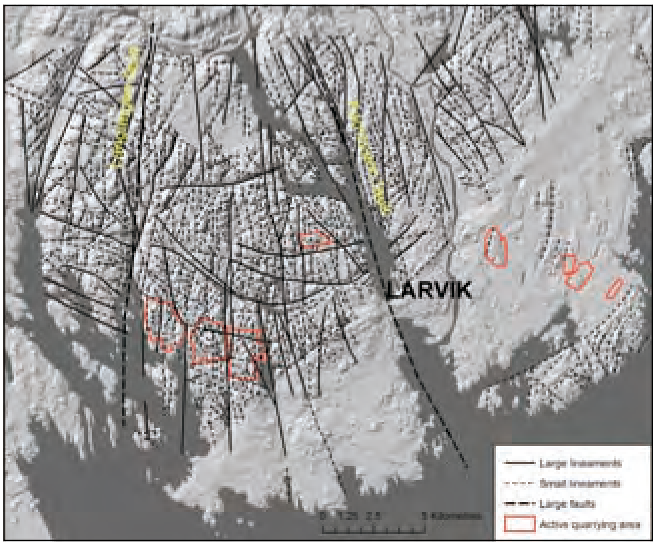


Figure 15. Lineament analysis of the larvikite area.

and/or second-order fractures may have its unique system of third- and fourth-order fractures differing from the neighbouring block. Partially, this seems to be related to a complex stress distribution in the larvikite that can vary from one hill to the next. Consequently, even within a small area, fracture and stress systems vary significantly from quarry to quarry. Not surprisingly, there is a general correlation between topography and fracturing—the topographic highs being composed of the most massive and least fractured larvikite. So, in most cases, we find the best deposits of larvikite on hills. However, even in the least fractured larvikite deposits other problems may be present, such as 'open cleavage', a term used by the quarrymen in Tvedalen. Open cleavage is most commonly seen on hilltops of massive, Tvedalen-type larvikite, and appears as subvertical, clay-coated fractures along the mineral orientation planes. Commonly, it only occurs in 5–15 m-wide zones below the terrain surface. The most likely interpretation of the open cleavage is that it is caused by erosional stress release. This also explains why it is mainly found in the relatively massive parts of the larvikite, where the lack of abundant pre-existing fractures makes the stress release take place along other planes of weakness, i.e., mineral alignment planes.

Dykes, pegmatites and shear zones

Dykes of different composition are found in most parts of the larvikite complex and are dominantly oriented between NE–SW and NW–SE. Most common are fine-grained larvikitic dykes. The dykes are generally a minor problem in the quarrying, except from a few areas where they are particularly abundant.

Pegmatites have a more severe impact on the larvikite quality. In particular, irregular bodies of pegmatite are difficult to predict and may cause serious problems for the quarrying not only due to their presence, but also due to the commonly associated alteration and discolouration (see above). Although pegmatites are found in all of the quarry areas, they are particularly common along the margin of the complex and especially in its western part, i.e., to the west and south of Langangen. The high density of pegmatites is reflected on the thorium anomaly map since pegmatites (Ihlen et al. 2006) and nepheline syenite intrusions (Dahlgren, unpublished data) appear to be more strongly enriched in thorium than the other rocks in the larvikite massif. This area is the type locality of thorium, and the mineral thorite, and the confinement of this element/mineral to the pegmatites was established early on by Berzelius (1829) and Brøgger (1890).

Closely associated with pegmatites and nepheline syenite dykes are ductile shear zones, formed more or less contemporaneously during a late stage of the magmatic evolution (Figure 17). Locally, protomylonitic zones, several metres in thickness, are developed.

Magmatic layering and mineral orientation

Magmatic modal layering is not a common aspect of the larvikites, but is abundantly observed in some parts of the area (Figure

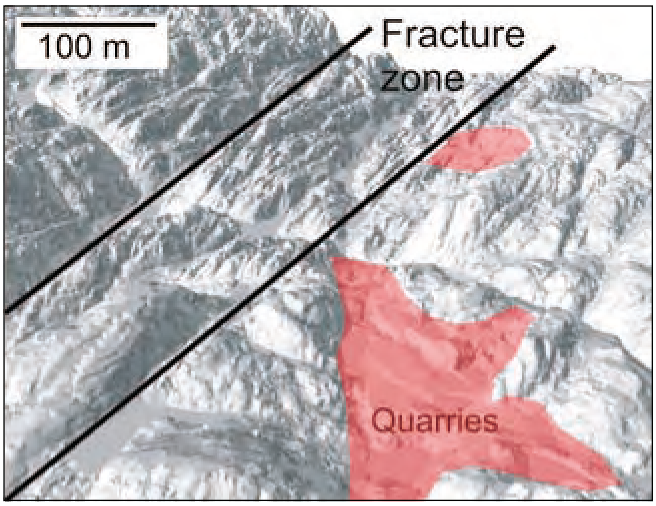


Figure 16. Digital terrain model of the topography in parts of the Tvedalen quarry area, displaying quarries located in a massive part of larvikite beside a large fracture zone.

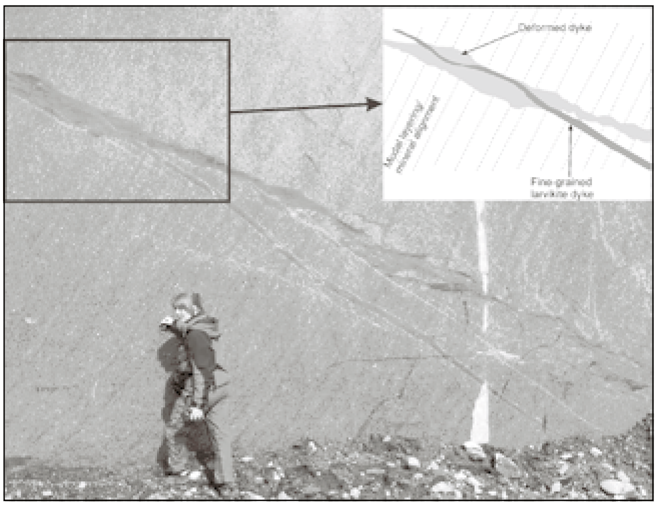


Figure 17. Larvikite dyke cutting shear zone at Malerød. Note mineral alignment and diffuse modal layering (concentration of mafic minerals) in the larvikite.

18). Since the presence of such layering by definition makes the rock inhomogenous, quarrying in such zones is generally avoided, except for the southern part of the Stålaker quarry area. The planar alignment of the feldspar is a more widespread feature of the larvikites, and of great importance in quarrying. The alignment plane represents both the primary splitting direction of the larvikite ('primary cleavage' or 'rift'[2]) and the plane along which the blocks should be cut in order to maximise the visible iridescence on finished slabs. Its strike follows the ring structures, and the dip varies from about 40° N to vertical. In certain areas where both modal layering and planar alignment can be seen, they are subparallel or slightly oblique to each other (Figure 19).

The importance of the planar alignment of feldspar may be illustrated with two examples. In the Klåstad area (Emerald Pearl variety), the average alignment plane dips 45° NW, but is quite diffuse with a wide scatter of orientations of the individual feldspar crystals, deviating up to 45° from the average. Thus, the blocks can be cut both vertically and horizontally without 'loosing' the iridescence completely. The possibility of varying cutting directions in such a way is favourable from the technical side of quarrying in the area.

In the Blue Pearl quarries in Tvedalen, the alignment of the feldspar is more strongly developed. Therefore, sawing cuts for slabs must be along this plane for the iridescence to be visible at all. The orientation of the plane is much steeper than at Klåstad (80–90° N). Therefore, it is more viable to follow this plane strictly in the quarrying, although the waste ratio becomes somewhat higher.

The examples above illustrate that even minor changes in the orientation and the nature of the preferred mineral orientation may have significant impact on the quarrying techniques and, thus, the economy of the quarries.

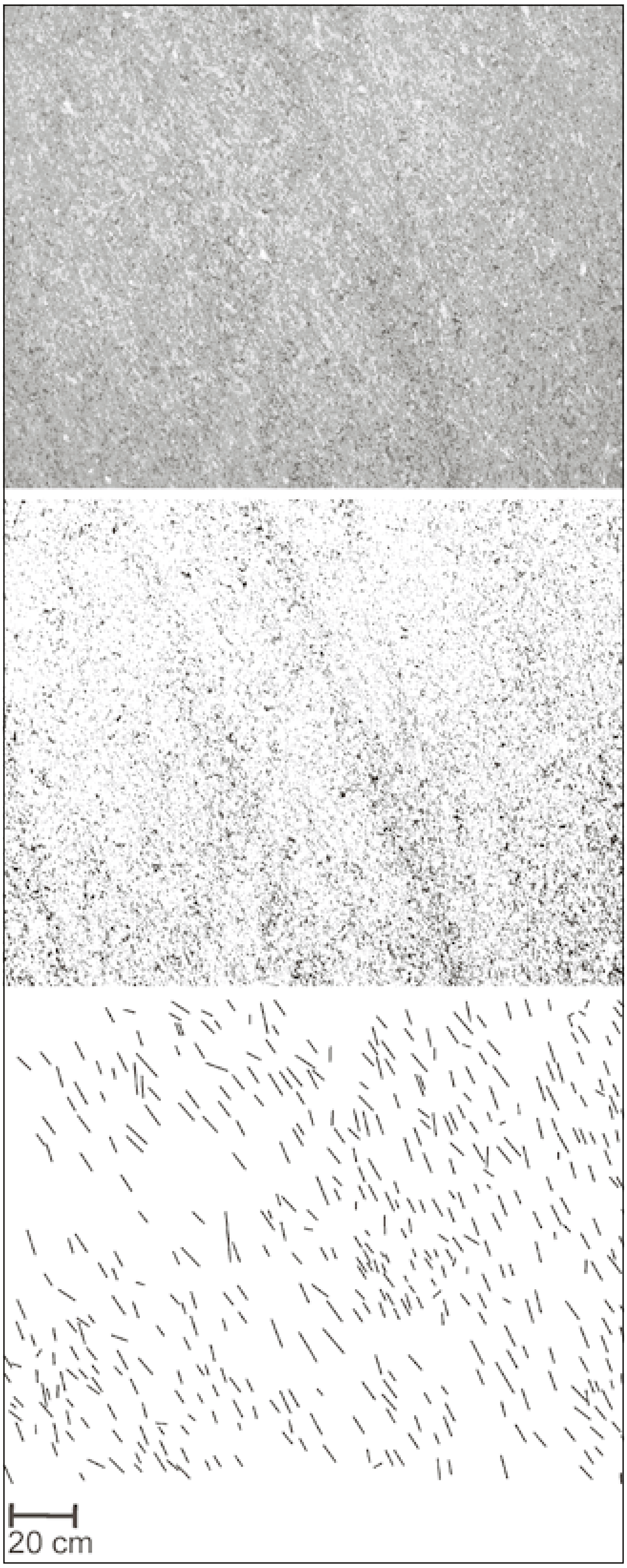


Figure 19 Mineral alignment and modal layering relations. Top: photo of quarry face at Malerød. Middle: distribution of mafic minerals in the same section, displaying diffuse, model layering. Bottom: feldspar orientation in the same section, being parallel to slightly oblique to the modal layering.

Figure 18. Modal graded layering and erosional contact in larvikite.

[2] Both terms are used by the stone industry to describe the best direction of splitting in rocks.

Synthesis: larvikite deposits in the short and long term

Towards a larvikite exploration model

The future well being of the larvikite industry depends on several factors, as illustrated in Figure 20. Most important is the international market. In particular, it is crucial to maintain a high price level to compensate for high production costs. This depends on the competition between the production companies and the aesthetic quality of the commercial blocks. The second issue relates to production techniques and strategies, efficient quarrying technology, waste handling and use (environmental aspects) and resource management (legal aspects). It is vital for the industry to continue to invest in state-of-the-art technology for improving block yield and reducing costs, and simultaneously meet more and more strict demands for environmentally friendly development.

The third issue, which is the subject of this paper, is the geological aspects—to secure that future production takes place where the geological conditions are most favourable. Based on the various features discussed above, these conditions can be summarised in an exploration model specifically applicable to the larvikite deposits (Figure 21). As shown in this figure, the first important question is the market value, in other words, whether the colour and structure of a certain subtype of larvikite meet the strict demands in the present-day market. Conversely, in cases where new commercial types are discovered, it is sometimes possible to adapt the market to the new material.

If the answer is 'yes' to the first question (Figure 21), there is a set of highly important geological factors that should be carefully evaluated, as described above. Clearly, the spacing and density of fractures and joints are important, as they are for all types of dimension-stone deposits. More specific to larvikite are the problems of alteration/bleaching and the occurrence of dykes, pegmatites and shear zones, as well as the nature and orientation of the mineral orientation plane. If these aspects turn out in favour of production and there is sufficient volume in the deposit, quarrying may be initiated. However, it is extremely difficult to predict the exact production costs and block yield accurately. A relative change of one percent in waste ratio may mean the difference between failure and success, and in many cases it is impossible to obtain such figures without full-scale quarrying operations. Therefore, regular evaluation of the aspects mentioned above is of vital importance. If, for instance, the discolouration in some parts of a quarry is critically high, it may be necessary to abandon that part before loosing too much money.

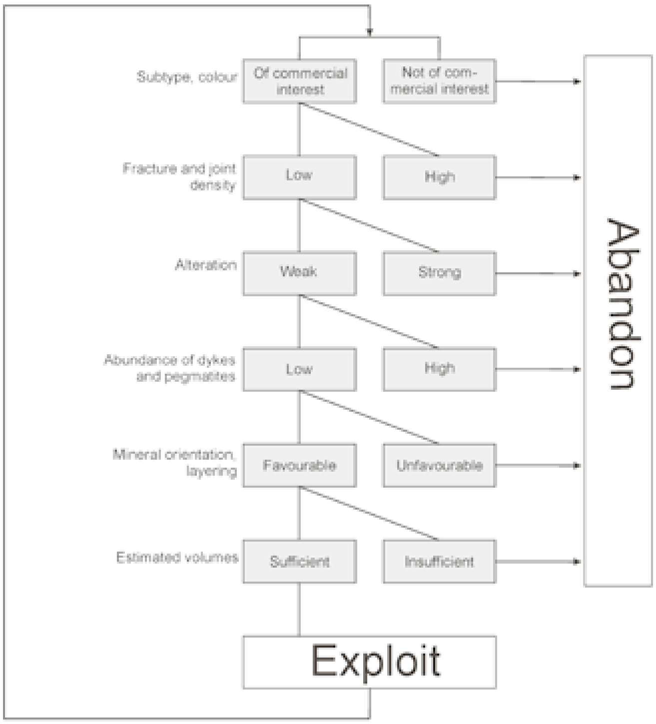


Figure 21. Exploration model for larvikite deposits.

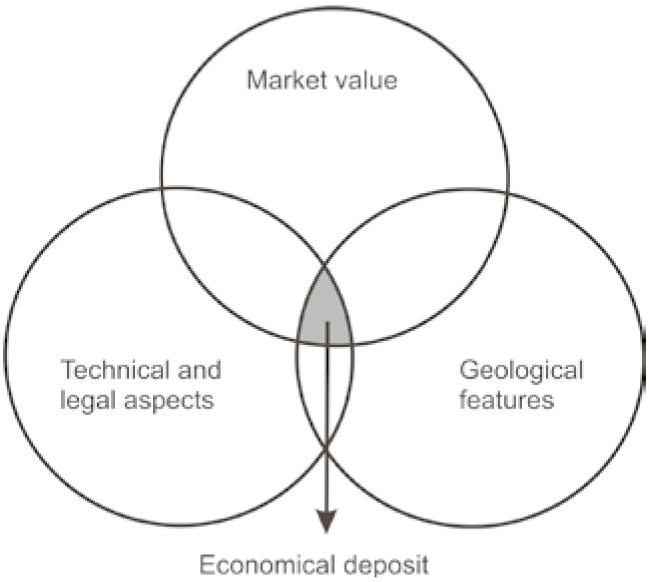


Figure 20. Aspects of economic evaluation of larvikite as dimension stone.

Addressing future reserves

The area around Larvik is experiencing rapid population growth and expansion of industry, tourism and infrastructure. Furthermore, since basically the whole area consists of larvikite bedrock, it is impossible to preserve all larvikite with iridescence for future exploitation without getting into conflict with other land-use interests in the region. This conflict between resources and infrastructure has caused a need for delineating the most important deposits in the area that can realistically be preserved for the future. By combining the field observations we have of larvikite types, colour, fracturing, alteration and morphology, we have delineated what we believe are the most important resources for exploitation in the future. In doing so, we have not only evaluated the larvikite types that are commercially interesting at the present time, but also included some subtypes which may represent an additional future reserve given a positive development of the market situation for larvikite. In Figure 22, the assumed exploitable resources of larvikite are shown, characterised according to short- or long-term reserves and importance; the latter concerns a combination of subtype and commercial value (colour) balanced against the occurrence of pegmatites, alteration and other quality-reducing features. The most important category is known reserves of commercial subtypes in production within or in the vicinity of active quarry areas, whilst the least important is exploitable deposits of larvikite with weak iridescence and thus unlikely to be put into production. The map in Figure 22 forms the basis for future management of the larvikite deposits.

While looking into the crystal ball, it is also interesting to make some estimates of remaining reserves of different types of larvikite. In Figure 23, we have made estimates of known, probable and speculative reserves of different varieties[3]. The calculations are based on the assumption of 2.5% (pessimistic) and 5% (optimistic) average block yield and quarrying depth down to 30 m below the topographic surface. Not surprisingly, the known reserves of the Tvedalen type are the largest in volume, i.e., between 7.5 and 15 million m^3. If the annual production continues as it is now (40–50,000 m^3 a year), this will mean reserves for somewhere between 160 and 330 years. Similarly, the known reserves for the Klåstad type (Emerald Pearl) are between 30 and 60 years, which is not much thinking in long terms. However, there may be large potential reserves further north, beneath the farmland. Since we do not know the quality of the larvikite in most of these areas due to the soil cover, more detailed investigation of the subsurface quality should be carried out not too far into the future, and hopefully contribute to a substantial increase of known reserves.

Although such reserve estimates are uncertain, they give us an idea of the lifetime of the different deposit types, and especially where one has to put efforts to secure future extraction of unique larvikite types. Furthermore, they point at some potential new deposits that can provide an addition to the larvikite palette in some more distant future, if the market situation permits. The estimates contribute to a generally raised awareness of the importance of the larvikite resources, and last but not least, the survey underlines the responsibility for building a good management regime for a national resource of global significance.

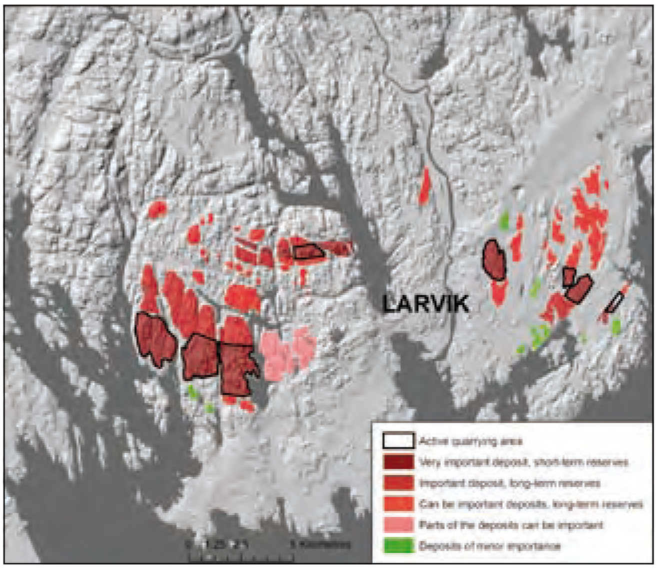


Figure 22. Distribution of larvikite deposits after their economic potential in the short and long term.

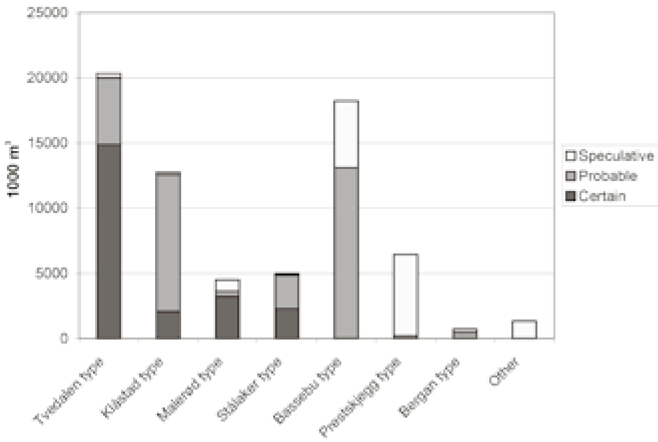


Figure 23. Reserve estimates of larvikite subtypes, in 1000 m^3 (net reserves, after subtracting estimated 95% waste).

Concluding remarks

The investigation of the dimension-stone potential of larvikite has revealed new information about important geological features controlling the commercial value of the stone and the connections between them. In particular, the role of tectono-magmatic processes in the formation of the larvikites seems to be crucial. The investigation started with obtaining an overview of the regional distribution pattern of larvikite, continued with combining these data sets with the most important structural and magmatic features that have high impact on the quality, and ended up with a distribution of deposits with potential economic importance in the short and long term. The investigation has also uncovered some new questions regarding the mechanisms behind the formation and emplacement of the larvikite complex. The contact relations between larvikite intrusions are more complex than previously assumed, and the contacts do not strictly follow the ring structures as described by Petersen (1978a). Another crucial issue is the overall structural pattern of the larvikite complex and the implications for modelling its formation. The overall relations between igneous layering, mineral orientation and syn-magmatic deformation still remain open.

[3] Larvikite subtypes or deposit areas not in production are classified as probable or speculative.

Clearly, although the larvikite complex has been the subject of research for more than 100 years, many unsolved scientific problems still remain.

Acknowledgements

The present paper is the result of several projects concerning investigations of larvikite resources over the last decade. Special thanks to Håvard Gautneb, NGU, for participation in the survey of the larvikites. Many other people are thanked for contributing with their knowledge in different ways: Reid Kvien for kindly letting us borrow his collection of polished samples of larvikite, Bjørn Willemoes-Wissing for SEM work, Christian Tegner (previous colleague at NGU) for hard work in the field, and finally, the larvikite companies for their hospitality. Peter Ihlen and an anonymous reviewer are thanked for constructive comments. The work has received funding from several sources: NGU, the counties of Buskerud, Telemark and Vestfold, Larvik municipality, Statens Vegvesen and the larvikite industry.

References

Barth, T.F.W. (1945) Studies on the Igneous Rock Complex of the Oslo Region II. Systematic petrography of the plutonic rocks. *Det Norske Videnskaps-Akademi i Oslo, Skrifter. I. Mat.-Naturv. Klasse,* **9**, 104 pp.

Beard, L.P. (1999) Data acquisition and processing – Helicopter geophysical surveys, Larvik, 1998. *NGU Report 1999.026*, 13 pp.

Berzelius, J. (1829) Undersøkning af et nytt mineral som innehåller en förut obekant jord. *Kongliga Svenska Vetenskaps-Akademiens Handlingar*, 1829, pp. 1–30.

Brøgger, W. (1890) Die Mineralien der Syenitpegmatitgänge der Südnorwegischen Augit- und Nephelinsyenite. *Zeitschrift für Krystallographie und Mineralogie*, **16**, I–XVIII + 1–235 (Allgemeiner Theil), 1–663 (Specieller Theil).

Dahlgren, S., Corfu, F. and Heaman, L. (1998) Datering av plutoner og pegmatitter i Larvik pluton-kompleks, sydlige Oslo Graben, ved hjelp av U–Pb isotoper i zirkon og baddeleyitt. Kongsberg mineralsymposium 1998, *Norsk Bergverksmuseum Skrift*, **14**, 32–39.

Dons, J.A. (1978) Terminology and history of investigations. *In* Dons, J.A. and Larsen, B.T. (eds.) *The Oslo Paleorift. A review and guide to excursions*, Geological Survey of Norway Bulletin, **45**, pp. 9–16.

Heldal, T. (2008) Norges nye nasjonalbergart: Nasjonalhelt og verdensborger. *GEO*, **02/08**, 10–12.

Heldal, T., Kjølle, I., Beard, L., Tegner, C. and Lynum, R. (1999) Kartlegging av larvikitt mellom Sandefjord og Porsgrunn. *NGU Report 1999.059*, 68 pp.

Ihlen, P.M., Raaness, A., Korneliussen, A., Skår, Ø., Müller, A. and Meyer, G. (2006) Rekognoserende undersøkelser av et utvalg potensielle mineralressurser i Fritzöe Skoger. *NGU Report 2006.030*, 19 pp.

Kjølle, I., Heldal, T. and Gautneb, H. (2003) Forekomster av larvikitt – ressurskart. *NGU Report 2003.066*, 9 pp.

Larsen, B.T. and Olaussen, S. (2005) *The Oslo Region. A study in classical Palaeozoic geology*. Field guide to NGF's Centennial field trip, May 26–28, 2005, 88 pp.

Mogaard, J.O. (1998) Geofysiske målinger fra helikopter ved Larvik, Vestfold, teknisk rapport. *NGU Report 1998.021*, 11 pp.

Muir, I.D. and Smith, J.V. Jr. (1956) Crystallization of feldspars in larvikites. *Zeitschrift für Kristallographie*, **107**, 182–195.

Neumann, E.R. (1978a) Petrogenesis of the Larvik ring-complex in the Permian Oslo Rift, Norway. *In* Neumann, E.R. and Ramberg, I.B. (eds.) *Petrology and Geochemistry of Continental Rifts*, D. Reidel Publ.Comp., Dordrecht, pp. 231–236.

Neumann, E.R. (1978b) Petrology of the plutonic rocks. *In* Dons, J.A. and Larsen, B.T. (eds.) *The Oslo Paleorift. A review and guide to excursions*. Geological Survey of Norway Bulletin, **45**, 25–34.

Neumann, E.R. (1980) Petrogenesis of the Oslo Region larvikites and associated rocks. *Journal of Petrology*, **21**, 499–531.

Neumann, E.R., Brunfelt A.O. and Finstad, K.G. (1977) Rare earth elements in some igneous rocks in the Oslo rift, Norway. *Lithos*, **10**, 311–319.

Neumann, E.R., Tilton, G.R. and Tuen, E. (1988) Sr, Nd and Pb isotope geochemistry of the Oslo rift igneous province, southeast Norway. *Geochimica et Cosmochimica Acta*, **52**, 1997–2007.

Nielsen, A.M. (2007) *En petrologisk og geokemisk undersøgelse af ringintrusionerne IV og V i larvikitkomplekset Norge*. M.Sc. thesis. Department of Earth Sciences, University of Aarhus, Denmark, 111 pp.

Oftedahl, C. (1948) Studies on the igneous rock complex of the Oslo Region. IX. The feldspars. *Det Norske Videnskaps-Akademi i Oslo, Skrifter. I. Mat.-Naturv. Klasse*, **3**, 71 pp.

Oftedahl, C. and Petersen, J.S. (1978) Southern part of the Oslo Rift. *In* Dons, J.A. and Larsen, B.T. (eds.) *The Oslo Paleorift. A review and guide to excursions*. Geological Survey of Norway Bulletin, **45**, 163–182.

Oxaal, J. (1916) Norsk Granitt. *Norges geologiske undersøkelse*, **76**, 220 pp.

Petersen, J.S. (1978a) Structure of the larvikite-lardalite complex, Oslo Region, Norway, and its evolution. *Geologische Rundschau*, **67**, 330–342.

Petersen, J.S. (1978b) Composite plutonic ring complexes: a strucutral characteristic and rift zone plutonism. *In* Neumann, E.R. and Ramberg, I.B. (eds.) *Petrology and Geochemistry of Continental Rifts*, D. Reidel Publ.Comp., Dordrecht, 217–229.

Ribbe, P.H. (1975) Exsolution textures and interference colors in feldspars. *In* Ribbe, P.H. (ed.) *Feldspar Mineralogy, Mineralogical Society of America, short course notes*, **2**, R-73–R-96.

Rosenqvist, I.T. (1965) Electron-microscope investigations of larvikite and tønsbergite feldspars. *Norsk geologisk tidsskrift*, **45**, 69–71.

Smith, J.V. and Muir, I.D. (1958) The reaction sequence in larvikite feldspars. *Zeitschrift für Kristallographie*, **110**, 11–20.