Eurogranites 2008 / IGCP 510 field trip 2008

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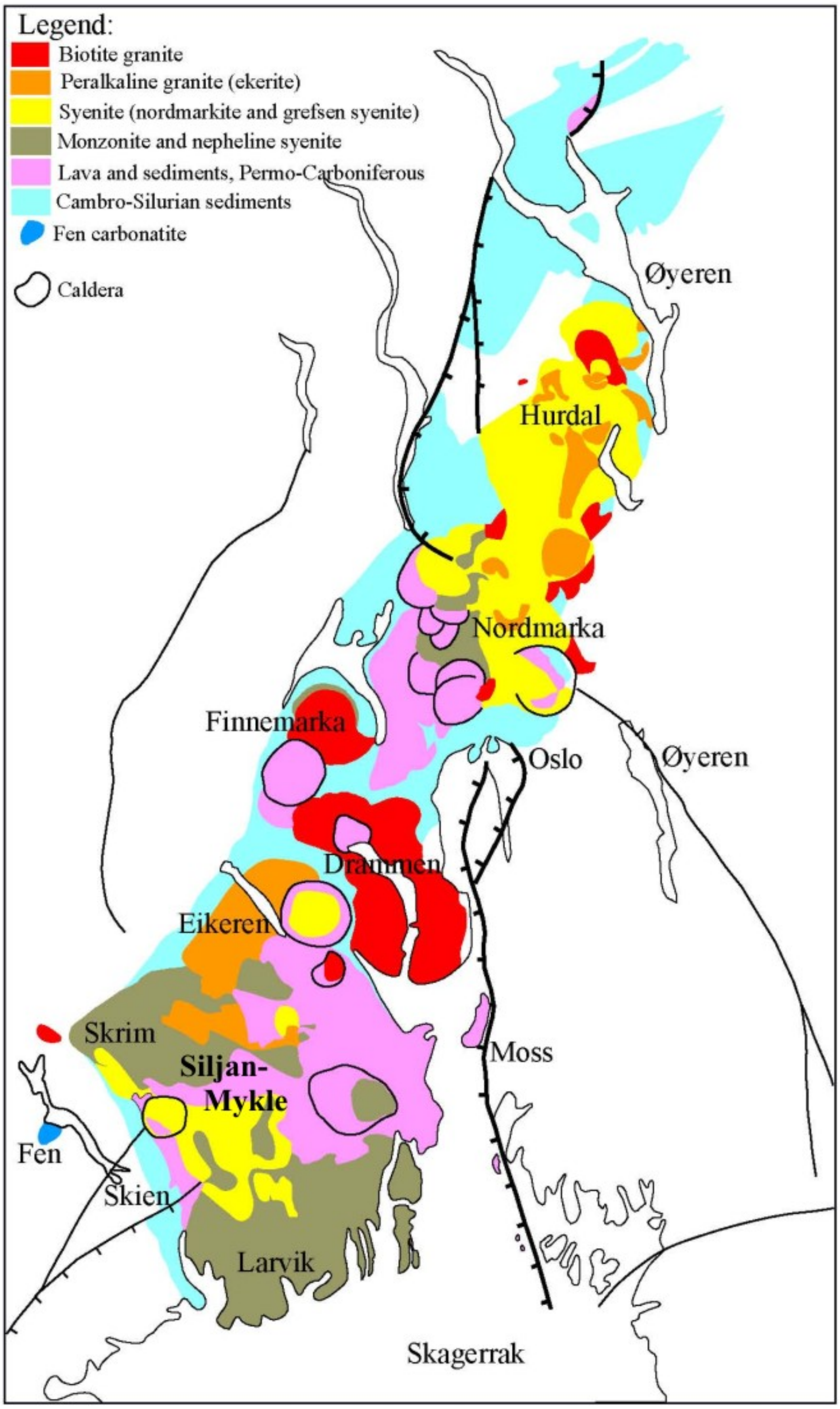


Fig. 1
Simplified geological map of the Oslo Graben

Part 1: An introduction to the Oslo Graben

The geology of SE Norway is uncommonly varied, with Precambrian basement rocks belonging to the Fennoscandian Shield (formed during the 1.50-1.60 ”Gothian” and 1.20-0.90 Sveconorwegian / Grenvillian periods), covered by sedimentary rocks of lower Paleozoic age and rift-related sedimentary, volcanic and intrusive rocks formed in late Carboniferous to Permian time.

The Oslo Region was ”discovered” by early 19th century geologists (L. von Buch, C. Lyell, B.M. Keilhau and others), and since the work by W.C. Brøgger and his contemporaries in the late 19th and early 20th century it has been recognized as a classical province of alkaline igneous rocks (Dons 1978). Since the time of the pioneers, geological research activities concerning different aspects of the region (geology, paleontology, stratigraphy, igneous petrology, metamorphic petrology, mineralogy, tectonics, geophysics etc.) has been continuous. A four-day excursion cannot do justice to all of this, and the *Eurogranites 2008 / IGCP 510* field trip will be concerned only with some aspects of the province, i.e. the felsic and intermediate magmatism in the southern part of the rift, and mainly with the intrusive rocks.

A note on nomenclature

Oslo is the capital of Norway (ca. 560 000 inhabitants). Oslo is the historical name of the town, but from 1624 to 1924 it was known as Christiania (also spelled Kristiania). The region with Paleozoic rocks around Oslo has traditionally been known as the *Oslo Region* (Oslofeltet in Norwegian, Oslogebiet in German), or prior to 1924, the Christiania Region. W.C. Brøgger published his monographs on the igneous rocks under the serial heading ”Die Eruptivgesteine des Christianiagebietes”, for the seventh and last of his volumes this was changed to ” Die Eruptivgesteine des Oslogebietes”. Today, ”Oslo Region” is used as a descriptive term referring in general to the area with Paleozoic rocks.

The *Oslo Graben* refers to the downfaulted blocks of Phanerozoic sediments, lavas and intrusions cutting through the Precambrian basement of the Fennoscandian Shield (Fig. 1). The Oslo Graben is itself made up by two graben segments: The *Akershus Graben* in the north, and the *Vestfold Graben* in the south (Fig. 2). The Oslo Graben forms part of the larger *Oslo Rift*, which includes the off-shore Skagerrak graben, and ties up with a system of post-Variscian rift structures in the North Sea and northwestern Europe (Wilson et al. 2004 and references therein, Larsen et al. 2008).

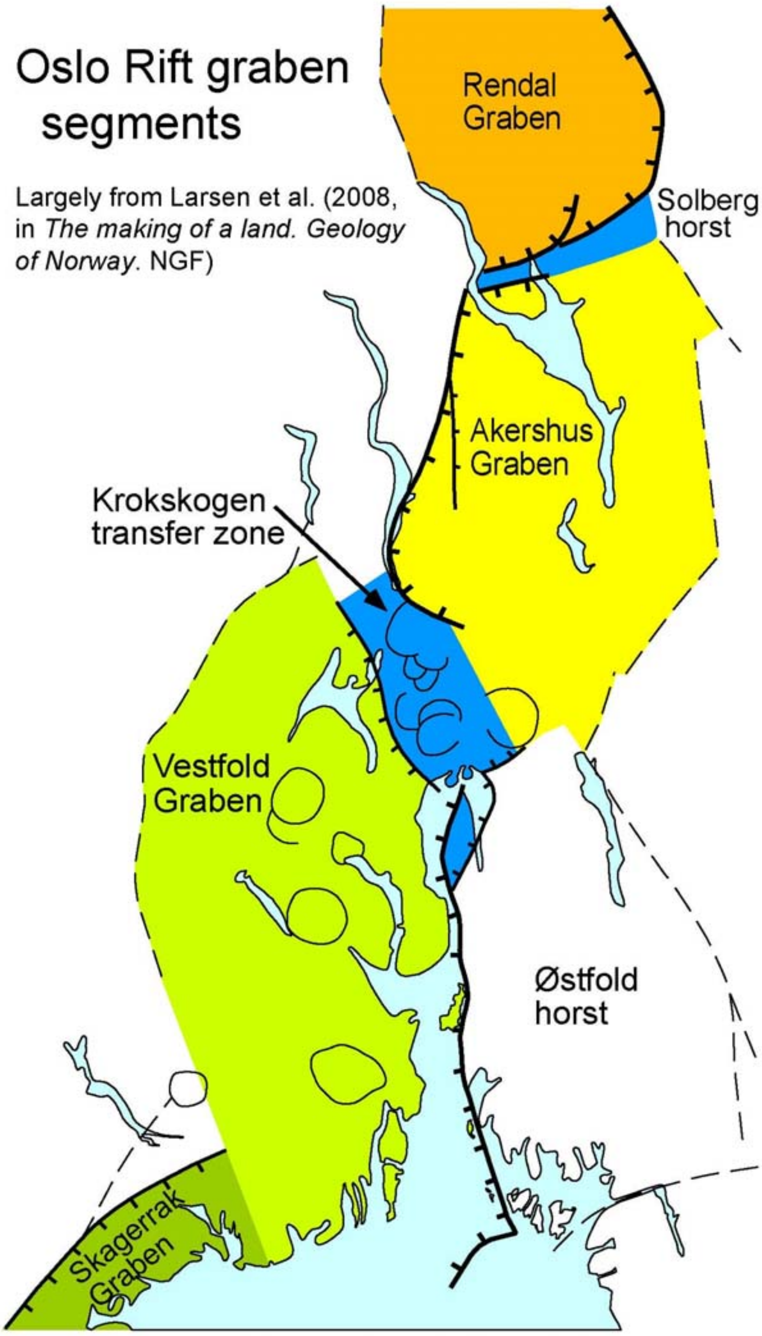


Fig. 2
Graben segments of the Oslo Rift

Tectonomagmatic evolution of the Oslo Rift

Two different aspects of the Oslo Graben have attracted the attention of geologists since the early 19th century: (1): The early Paleozoic sedimentary sequence and (2): The igneous and minor sedimentary rocks related to late Paleozoic rifting.

Early Paleozoic marine shales and limestones are preserved within the Oslo Graben (Worsley et al. 1983, Owen et al. 1990). Prior to rifting, such rocks must have covered large parts of southwestern Fennoscandia. The sedimentary rocks were folded during the Caledonian orogeny. The youngest early Paleozoic sedimentary rocks make up an up to 1250 m thick redbed sequence (the Ringerike Group, Worsley et al. 1983). By the late Carboniferous, the early Paleozoic sedimentary rocks had been eroded down to a peneplain, and a thin sequence of continental sediments (conglomerate, sandstone, shale) of upper Westphalian age (the Asker group) was deposited with an angular unconformity to the underlying Silurian sandstone. The presence of thin limestone units in the Asker Group indicates marine transgression from the south or east (Olaussen et al. 1994, Larsen et al. 2008).

The late Paleozoic evolution of the Oslo Rift can be divided into five or six distinct stages (Ramberg and Larsen 1978, Neumann et al. 2004, Larsen et al., 2008) Constraints on timing of events is provided by a large set of Rb-Sr isochron ages (see Sundvoll et al. 1990), which are now slowly being superseded by U-Pb ages, mainly from ziron (Table 1). In general, U-Pb geochronology seems to indicate narrower time intervals for each of the tectonomagmatic stages, and in general marginally older ages than suggested by Rb-Sr isochrons.

Table 1 Tectonomagmatic stages in the Oslo Rift			
	Products	*Stratigraphic or Rb/Sr age ranges*	*U-Pb age ranges*
1: Pre-rift stage	Asker group	Upper Westfalian (ca. 300-312 Ma)	< 319 Ma
2: Initial rifting stage	Basaltic volcanism	304-291 Ma	(305)-299 Ma
3: Main rifting stage	Intermediate lava (Rhomb Porphyry), larvikite intrusions	294-276 Ma	298-292 Ma
4: Central volcano stage	Calderas, diverse volcanic rocks, ring-dikes	280-243 Ma	
5: Batholith stage and 6: Terminal stage	Larvikite, syenites, granites	273-241 Ma	286-272 Ma

Sources: Sundvoll et al. (1990), Pedersen et al (1995), Dahlgren et al. (1998), Neumann et al. (2004), Haug (2007), T. Andersen (unpublished data).

S*tage 1*: The *pre-rift evolution* is characterized by depostion of the Asker group in a delta environment. A maximum age limit for deposition is given by a 319±5 Ma ID-TIMS age of a detrital zircon (Dahlgren and Corfu 2001), which agrees with fossils indicating an upper Westphalian (300-312 Ma) age of deposition for the Asker Group (Olaussen et al. 1994). A significant contribution of Variscian material to the deposits has been claimed from detrital zircon ages (Dahlgren and Corfu 2001), but the set of U-Pb data from detrital zircons is insufficiently large to positively rule out even a dominant contribution from nearby sources within the Fennoscandian shield (Andersen 2005).

Stage 2: Initial rifting. The oldest volcanism within the Oslo Graben produced basaltic lavas (B1) which form thick sequences in the Vestfold Graben, and which thin northwards and die out around Oslo. These lavas have been dated to late Carboniferous to earliest Permian ages, but they are pre-dated by a series of sills of trachyandesitic to rhyolitic composition which intrude the Asker group and underlying lower Paleozoic sedimentary rocks. The maximum Rb-Sr age obtained from these also indicates a latest Carboniferous age (Sundvoll et al. 1992).

Stage 3: In the *main rifting stage*, the Oslo Graben subsided, and large volumes of rhomb porphyry (trachyandesite, latite) and minor basalt erupted by fissure eruptions. The composite Larvik pluton intruded in this stage, and has been dated to 298-292 Ma by ID-TIMS U-Pb on zircons (Dahlgren et al., 1996, 1998).

Stage 4: In the *central volcanoe stage*, volcanic activity was concentrated on distinct volcanic centres with local trends of magmatic evolution, terminating in caldera collapse. The central volcanoes are preserved as between 15 and 20 caudron structures, representing sections through subvolcanic magma chambers, ring-dike systems and downfaulted blocks of volcanic rocks. Rb-Sr ages suggest a relatively long duration of this stage (ca. 280-240 Ma), unfortunately, U-Pb ages are not yet available for rocks formed in the central volcano stage.

Stage 5: Emplacment of the intermediate-felsic batholiths. This is the part of the rift evolution that will receive most of the attention during Eurogranites 2008 / IGCP 510. In the final stage, the large intrusions of syenitic to granitic composition were emplaced, as were many smaller larvikite intrusions (the Larvik pluton itself intruded earler, in Stage 3). LAM-ICPMS U-Pb ages for different intrusive members of the Drammen biotite granite pluton suggest ages in the range 272-286 Ma (Haug 2007), whereas larvikite and syenite in the Sande intrusion in the northern part of the Vestfold graben yield ages around 282±3 Ma (Andersen, unpublished data). Some students of the Oslo Rift (e.g. Larsen et al. 2008) regard the youngest granitic intrusions and late dikes as belonging to a distinct, terminal stage of evolution (Stage 6 in Table 1).

Plutonic rocks of the Oslo graben

The plutonic rocks of the Oslo graben are distributed in three main complexes, geographically separated by outcrops of Permian lavas and Cambro-Silurian sedimentary rocks (Fig. 1). The northern Akershus graben segment is occupied by the Nordmarka-Hurdalen batholith of mostly syenitic and granitic alkaline rocks and some intrusions of biotite granite and monzonite. Biotite granites of the Drammen and Finnemarka batholiths dominate the central part of the Oslo Graben (northern part of the Vestfold Graben). These batholiths cover areas of 650 and 125 km^2 respectively, and the Drammen batholith is the largest granitic complex in the rift. The largely monzonitic batholiths Larvik pluton and the compositionally more diverse Siljan-Mykle complex occupy the southern and central parts of the Vestfold graben segment.

The petrographic nomenclature used for plutonic rocks in the Oslo graben has been heavily influenced by W.C. Brøgger (e.g. Brøgger 1906), who introduced a large number of locally defined rock names, not all of which appear to have been well justified. Some of his more obscure terms have mercifully been discarded even by local geologists (e.g. "pulaskitic ekerite" – literally a nepheline-bearing alkali granite (!), but used to denote a local variety of quartz- and nepheline free alkali feldspar syenite in one of the plutons). However, any geologist working in or visiting the Oslo graben must learn to live with local rock names such as *larvikite*, *lardalite*, *ekerite* and *nordmarkite*. These are deeply entrenched in the literature, and are unlikely to be replaced by their approved QAFP or TAS classification equivalents in the forseeable future. Definitions of the local petrographic terms are summarized by Le Maitre et al. (2002).

Larvikite

According to the IGUS Glossary of Igneous Rock names, larvikite is *"a variety of augite syenite or monzonite consisting of rhomb-shaped ternary feldspars (with a distinctive schiller), barkevikite, titanian augite and lepidomelane. Minor nepheline, iron-rich olivine or quartz may be present"* (Le Maitre et al., 2002). Larvikite and associated rocks such as lardalite (nepheline-rich larvikite), kjelsåsite (plagioclase-rich larvikite) and tønsbergite (red, quartz-bearing larvikite) make up a family of intermediate intrusive rocks characteristic of the Oslo Rift. In terms of normative composition, larvikite qualifies as monzonite to monzodiorite, but because of its peculiar feldspar mineralogy it has proved difficult to classify in terms of QAFP components (c.f. definition above).

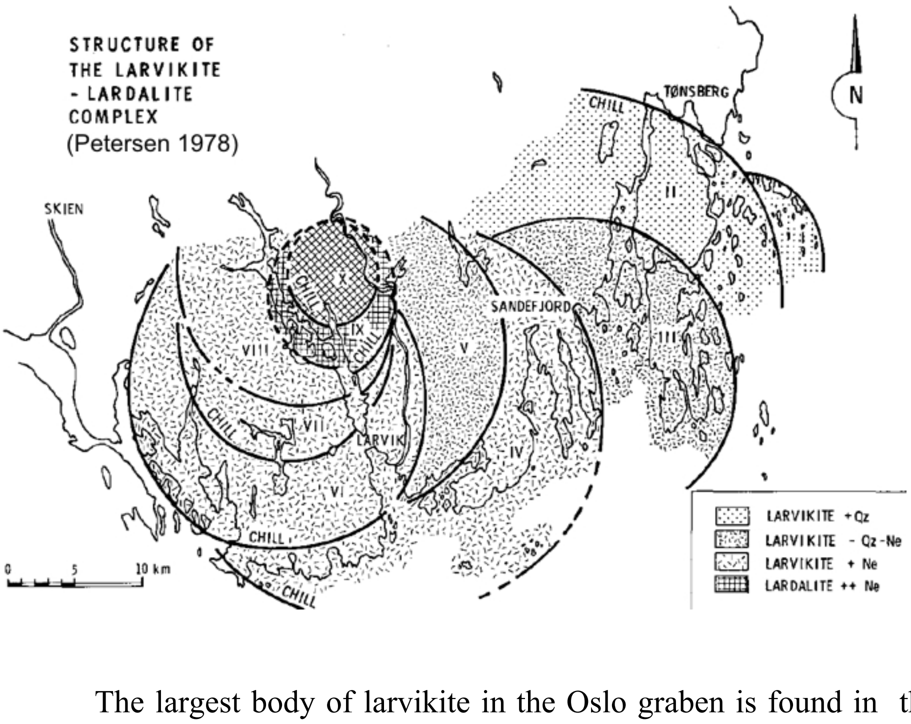


Fig. 3
Simplified geological map of the Larvik plutonic complex, from Petersen (1978). The zones marked from I to X are progressively younger intrusive members of the complex.

The largest body of larvikite in the Oslo graben is found in the composite Larvik pluton which makes up the southernmost part of the on-shore graben. This complex was emplaced as a series of ring-shaped intrusions with internal intrusive contacts marked by chill-zones (Petersen 1978). The intrusive centre migrated westwards and northwards with time (Fig. 3), at the same time the compostion changed from quartz normative, through silica saturated to olivine- and nepheline bearing varieties. The youngest intrusive members of the complex are lardalite (nepheline monzonite, zones IX and X in Fig. 3) and nepheline syenite / foyaite crosscutting these.

Larvikite makes up a significant component in the Siljan-Mykle complex, where it belongs to the first period of magma emplacement. It is furthermore found in the Nordmarka-Hurdal batholith and in several of the smaller composite intrusions (e.g. Sande pluton, Andersen 1984). Emplacent of larvikite thus spans stages 3 and 4 of the rift evolution.

Whereas larvikite varieties containing primary plagioclase and alkali feldspar are known (e.g. in the Sande pluton, Andersen 1984), the most characteristic mineralogical feature of larvikite is the presence of a partly exsolved anorthoclase feldspar. In some varieties, the spacing of cryptophertitic exsolution lamellae causes selective diffraction of blue and green spectral colours, which causes the very characteristic schiller of ornamental larvikite (Rosenqvist 1965).

Trace element distribution patterns and radiogenic isotopic signatures of larvikite (and its rhomb porphyry extrusive equivalent) point towards an origin from a mildly alkaline mafic mantle-derived parent magma (Neumann et al. 2004 and references therein). If so, extensive evolution by fractional crystallization at crustal levels is necessary (Neumann 1980). The range of compositions observed within the Larvik pluton (from mildly quartz normative to strongly nepheline normative compostions) is explicable by polybaric fractionation combined with density filtering in the crust (Neumann 1980).

Fig. 4
Larvikite in use: The use of larvikite as a building stone is beautifully illustrated by the University of Oslo central library building, which is faced with dark ”Emerald Pearl” larvikite from Klåstad, Tjølling.

The larvikite industry. The schiller effect of larvikite feldspar has made the rock into a very popular dimensional- and ornamental stone (Selonen and Suominen 2003). Examples of its use in buildings and sculpture can be found all over Oslo, including the Blindern campus (Fig. 4). Dimension stone has been produced in the Larvik pluton since the 1880s. Today ca. 30 individual quarries are in operation, exporting larvikite for ca. 500 MNOK/ year (Heldal et al. 2008). The feldspar in economically interesting varieties of larvikite should have a well-developed schiller-effect, and its fracture pattern should allow quarrying of large, homogeneous blocks. Several distinct larvikite types are recognized within the complex (Fig. 5), the most economically interesting of which are the dark ”Emerald Pearl” or Klåstad type (Fig. 4), the bluish grey ”Marina Pearl” or Stålaker type and the bright blue ”Blue Pearl” or Tvedal type. All of these form part of zones IV, V and VI in the intrusive chronology of Petersen (1978). In the 19th and early 20th century, the dark red larvikite variety known as tønsbergite was also widely used in architecture, and central Oslo shows many good examples (e.g. the Freemasons' hall).

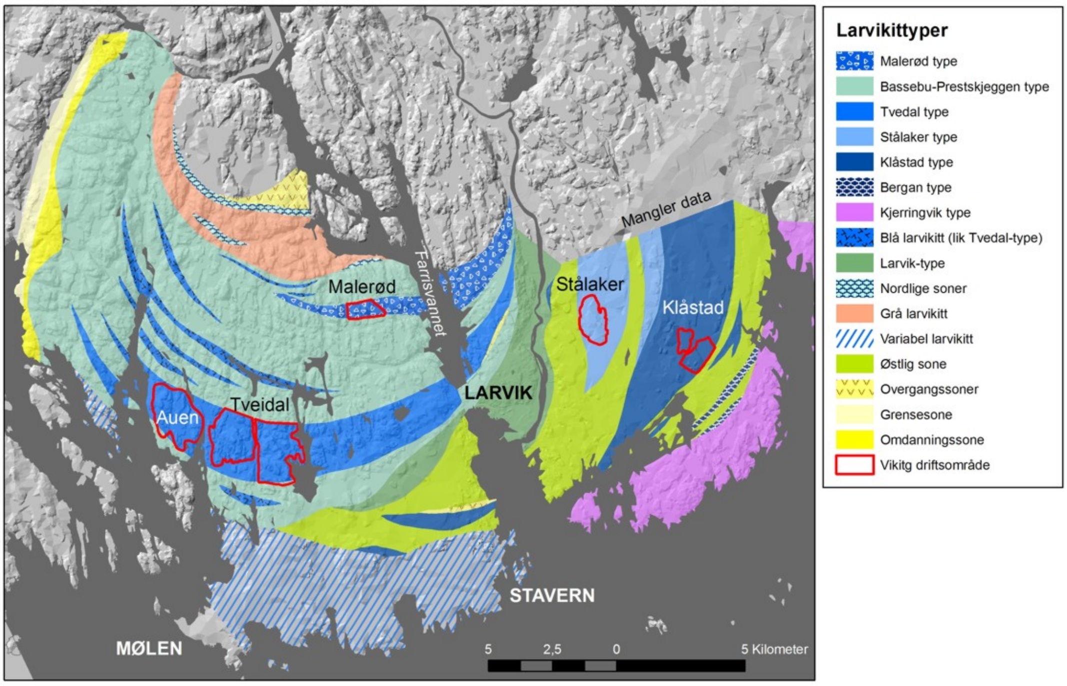


Fig. 5
Distribution of larvikite types and quarrying districts within the Larvik pluton. Based on field studies by the Geological Survey of Norway (Heldal et al. 2008 and http://www.ngu.no/upload/Georessurser/Naturstein/Forekomster/Larvikittforekomster/fig9.jpg).

Most larvikite lacks a well-developed "cleavage" (in the stone-masons' sense), which complicates quarrying. Today, large blocks are taken out by wire-sawing (Fig. 6). Only small amounts of larvikite is processed locally, and most is exported as raw blocks. Blocks for export should preferrably be larger than 4 m^3, and free of cracks, veins, alteration zones and pegmatites. This unavoidably leads to a large amounts of waste, with most quarries having a waste percentage of 90 % or more. Some of the waste larvikite is crushed for rock aggregate, or used as blocks for coastal protection or in drystone walls – a large fraction, however, is still dumped as waste close to the quarries.

Fig. 6
Quarry landscape from the Sagåsen quarry, Porsgrunn. This quarry produces the blue, iridescent variety known by the trade name "Blue Pearl", or as the Tvedal type. Quarrying is done by the wire-sawing method.

Syenite

Several different varieties of syenite are found in the Oslo graben. The best known and most widespread is the miarolitic aegirine-augite and/or alkali amphibole bearing quartz alkali feldspar syenite known as *nordmarkite* (Brøgger 1906). This rock type is a dominant component in the Nordmarka-Hurdal batholith in the Akershus graben (Sæther 1962), but is also found in composite intrusions in the Vestfold graben. The pale pink syenite used in many buildings and monuments in Oslo is not nordmarkite, but a true syenite or quartz syenite occuring in an intrusive body in the hills immediately north of the city. It is usually referred to by the local name "*Grefsen syenite*", from its type locality in the Grefesnåsen hill. This rock type is a medium-grained, miarolitic syenite to quartz syenite which contains grey plagioclase and / or anorthoclase feldspar rimmed by pink microcline; its characteristic dark silicate minerals are biotite and amphibole.

Investigations in the Siljan-Mykle complex in the 1980s and 90s has lead to the identification of other types of syenitic rocks which appear to have escaped the attention of Brøgger and his fellow early 20th century petrographers (Andersen and Sørensen 2003, Andersen et al. 2004a). These include some "missing links" in the petrographic spectrum (e.g. a porphyritic syenite that appears to bridge the compositional gap between larvikite and nordmarkite).

Granite[1]

Peralkaline granite with arfvedsonite or aegirine as charactieristic dark minerals (ekerite) makes up the Eikeren pluton in the Vestfold Graben, but also occurs in composite batholiths with monzonitic and syenitic rocks, and commonly show gradual transitions into these rock types, especially in the Akershus Graben. Gaut (1981) suggested a two-fold division of the *biotite granites*. He classifed relatively early intrusions without transitions to other rock types as BG1 and late intrusions intimately associated with syenitic rocks as BG2. The mildly peraluminous Drammen granite, spatially isolated from other intrusive rocks, is the most prominent example of a BG1. Mapping by Stenstrop (1989), however, has shown that the most widespread rock type within the Finnemarka batholith is metaluminous to peralkaline BG2 and that peraluminous to metaluminous BG1 is confined to the southern part of the batholith. The northern Finnemarka BG2 is rimmed by intermediate intrusives, and Stenstrop (1989) suggested that the granitic rocks are derived from mafic and intermediate magmas by fractional crystallization.

The members of the BG1-category, including the Drammen batholith, are mostly older than the alkaline syenites and granites (Rb-Sr isochron ages of ca. 280 Ma versus 270-240 Ma, respectively; Jacobsen and Raade 1975; Sundvoll 1978; Gaut 1981; Rasmussen et al. 1988; Sundvoll et al. 1990). It is therefore possible that these biotite granites are largely unrelated petrogenetically to the the main Oslo Rift magmatic series, and several authors including Barth (1954, 1962), Killeen and Heier (1975), Ramberg (1976) and Neumann et al. (1977), suggested that they were formed by crustal anatexis. $^{87}Sr/^{86}Sr$ initial ratios, however, indicate that the source regions for the BG2 had relatively low time-integrated Rb/Sr-ratios, almost indistinguishable from the other intrusives (Sundvoll 1978). Based on a reconnaissance Sr-Nd-isotopic survey, Jacobsen and Wasserburg (1978) concluded that none of the felsic rocks, including the biotite granites, could have formed by crustal melting. Hf isotope data from zircons further support the mantle-derived nature of the parent magma, but also point to ca. 1.5

[1] See also page 27, below.

Ga rocks of composition and history similar to metarhyolitic rocks of central south Norway as a source of contamination (Haug 2007).

The apparent contradiction between mildly peraluminous major element chemistry and isotopic mantle signatures of the southern part the Finnemarka and Drammen complexes was addressed by Trønnes and Brandon (1992). They found that the southern part of Finnemarka is indistinguishable from the most primitive mafic to intermediate rocks (Neumann et al. 1988) in terms of the Sr-Nd-isotopic compositions and that samples from the northern part of the Drammen complex lies on mixing lines with lower crustal components (20–50% lower crustal components). All of the analysed samples from these two complexes are characterized by less radiogenic Pb-compositions than the most primitive mafic to intermediate rocks (Neumann et al. 1988). In particular, the Drammen and Finnemarka batholiths seem to record a time-integrated lithospheric Th-depletion confined to the northern part of the Vestfold graben segment. The central and southern part of the Drammen batholith have greatly elevated $^{87}Sr/^{86}Sr$ -ratios due to significant upper crustal contamination and/or interacition with upper crustal fluids.

Nepheline-bearing plutonic rocks

The main occurrences of silica- undersaturated plutonic rocks in the Oslo graben are in the northern part of the Larvik pluton, but minor bodies of nepheline syenite are also found in the Siljan-Mykle complex (Andersen and Sørensen 1993) and in the Nordmarka-Hurdal massif (Sæther 1962).

Lardalite is a nepheline monzonite carrying a ternary feldspar similar to that of the larvikite. Normative Ne contents are in the range 20-25 % (Neumann 1980). Lardalite makes up the two youngest intrusive members in the Larvik pluton (IX and X in Fig. 3), which are the largest volumes of nepheline-bearing intrusive rocks in the Oslo Graben. Lardalite is undoubtedly related to the associated larvikite, but the nature of the relationship is still not properly understood. Positive Eu anomalies in samples of lardalite suggest that accumulation of feldspar in a strongly silica undersaturated magma has been one of the processes involved (Neumann 1980).

The lardalite massif is intruded by different types of syenitic rocks, whose genetic relationship to each other and to larvikite remains unclear (Neumann 1980). A prominent rock-type among these is a white, medium-grained nepheline syenite which was named *hedrumite* by Brøgger (1906). This rock type commonly contains minor amounts of blue to pale bluish grey sodalite, and locally ranges into sodalite foyaite (Oftedahl and Petersen 1978). In places it has a well-developed trachytoidal texture.

The Raubern nepheline syenite in the Siljan-Mykle complex is one of several large xenoliths of fine-grained nepheline syenite enclosed by younger, quartz-bearing intrusive rocks (Andersen and Sørensen 1993). This rock type is less alkaline than other nepheline syenites in the graben, and hence contains pyroxenes and amphiboles that are richer in Al than is common in the region, as well as late-magmatic garnet (see locality description, below). The nepheline syenite in the Siljan-Mykle complex belongs to the first stage of magma emplacement in the complex, together with larvikite and gabbroic rocks. These have been intruded by younger, syenitic to alkali granitic intrusions.

The syenite and nepheline syenite pegmatites

The pegmatites in and around the Larvik pluton have been known as a source of rare minerals for almost two centuries (Andersen et al. 1996, Raade et al. 1980, Larsen 1996). The monumental work by Brøgger (1890) established these rocks and their constituent minerals as classics of their kind. In his monograph, Brøgger aimed to characterize the mineralogy of the pegmatites (including first description of several new species), and to understand their genesis. Since his time, much research has been done on minerals and mineral groups, but less on the mineral assemblages and the petrology of the pegmatites. Some of the pegmatites show an agpaitic mineralogy, with the presence of Na-Ca-Zr silicate minerals (eudialyte s.l., catapleiite, wöhlerite, rosenbuschite, hiortdahlite, låvenite, grenmarite and others) instead of zircon. These are the only examples of agpaitic rocks in the Oslo Rift, which represent an important and so far not fully understood part of the magmatic evolution in the rift.

Syenite pegmatite dikes are encountered throughout the whole Larvik plutonic complex and in the basaltic rocks close to the border. The syenite pegmatites in the southern part of the Oslo Region approaches agpaitic mineralogy, specially along the south-western border. The pegmatites occur as fissure filling dikes with more or less sharp borders against the wall-rock. Brøgger (1890) distinguished between two types of pegmatites: A western type occurring in the Langesundsfjord area, and an eastern type occurring in Brunlanes-Larvik-Tjølling-Sandefjord area. The latter type was previously called Stavern-type dikes (*Fredriksvärn-type* by Brøgger). These pegmatites may attain large dimensions. Dikes with a thickness of 1 m are quite common, and some dikes are 10-20 m thick and 120 m long. They have sharp borders against the wall-rock, and are usually coarse- to giant-grained, with feldspar individuals up to 2 m in size. The main minerals are greyish to reddish microcline (microperthite to cryptoperthite, often schillerising) and black amphibole (hastingsite, magnesiohastingsite or magnesiokatophorite) ± nepheline (often altered to *spreustein*) ± magnetite ± biotite ± a suite of accessory minerals. The amount of accessory minerals is, with few exceptions, rather limited. The pegmatites of the western type, i. e. in the border zone on the island in the Langesundsfjord and on the mainland in the immediate vicinity of the fjord, occur as more or less irregular veins, often not particularly coarse-grained. This type of pegmatites show a more agpaitic mineralogy than the previous type, and are classified as nepheline syenite pegmatites. The main minerals are white or greyish microcline, nepheline (often more or less altered to *spreustein*) ± aegirine ± ferro-edenite (*barkevikite*) ± magnetite ± biotite. In addition, a large variety of accessory minerals may be present, and the abundance of Zr-, Ti-, Nb-, REE- and Be-minerals are conspicuous. The basaltic rocks close to the border of the larvikite massif are locally transected by huge pegmatite dikes, mainly of the western type. In most syenite pegmatite dikes, apart from the primary, magmatic stage, a secondary, hydrothermal stage is discernible. The hydrothermal stage is usually characterised by extensive zeolitisation and alteration of the magmatic minerals, and with crystallisation of low-temperature hydroxides and hydrous silicates. Many of the rare REE-minerals and Be-minerals belong to this stage of pegmatite formation. A few minerals have crystallized as the result of supergene prosesses, but is never the less part of the complete history of the syenite pegmatite dikes in the Larvik plutonic complex.

Geochemistry of igneous rocks in the Oslo Graben

Major element variation

The igneous rocks of the Oslo Graben range in composition from gabbro / basalt to granite / rhyolite. A vast majority of rocks plot within the alkaline field in a total-alkali vs. silica diagram (Fig. 7).

The B1lavas span a range from nephelinite and tehprite to quartz tholeiite. The most strongly alkaline lavas are found in the southwesternmost part of the Vestfold Graben (the Skien basalts). The alkalinity of the B1 lavas decreases with time and with position along the rift axis. In the north-central part of the Vestfold Graben they are mildly alkaline to subalkaline, and the northernmost basalt near Oslo is quartz tholeiitic (Neumann et al. 2004 and references therein).

Rhomb porphyries and larvikites plot within the trachyandesite field of the TAS diagram, but in general Na_2O-2.0<K_2O, which suggests that *latite* is a more appropriate TAS term (Le Maitre et al. 2002).

The felsic intrusive rocks belonging to the late stages of rift development range in composition from trachyte to rhyolite.

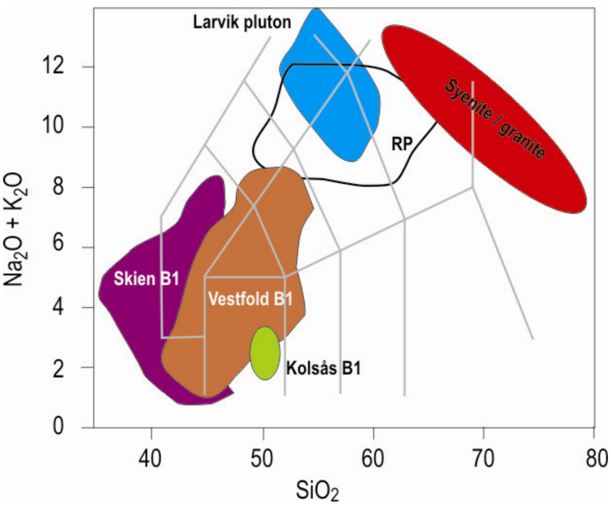


Fig. 7
Compilation of whole-rock compositions of lavas and intrusive rocks from the Oslo Graben in a total alkali – silica diagram (wt %). From Neumann et al. (2004). Grey lines: Boundaries of the IUGS TAS classification (Le Maitre et al. 2002).

Trace element and isotopic data

Mafic rocks (MgO> 5.0 wt %) show trace element signatures compatible with an OIB-like upper mantle source with variable enrichment in LILE, positive anomalies in Ta and Nb and negative anomalies in P, Zr and Hf (Neumann et al. 2004). The tholeiitic B1 basalt from Kolsås near Oslo is less LILE enriched, and is mildly depleted in Nb and Ta, compatible with crustal contamination.

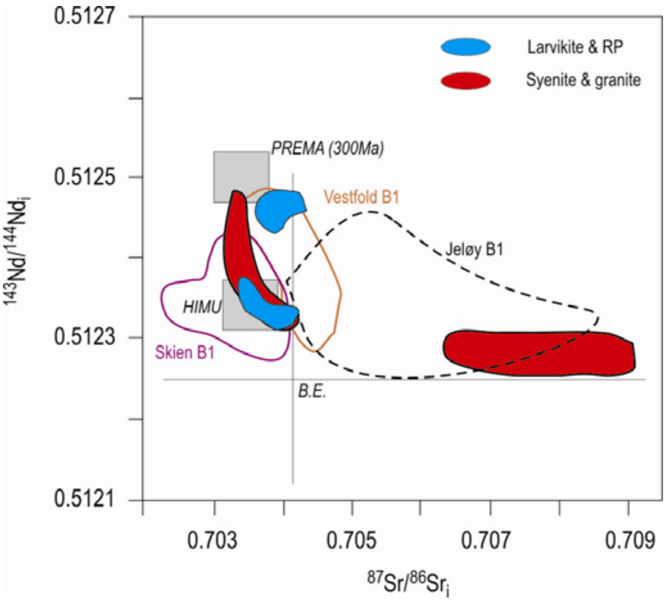


Fig. 8
Ranges of Sr and Nd isotope isotope data from mafic and felsic igneous rocks from the Oslo Graben, from Neumann et al. (2004).

Initial Sr and Nd isotopic characteristics range from compositions close to PREMA at 300 Ma for alkaline mafic rocks ($\varepsilon_{Nd} \approx +5$, $^{87}Sr/^{86}Sr_i = 0.703$ to 0.704). Many of the intermediate rocks (larvikite, rhomb porphyry) overlap with these, whereas syenites and granites show trends towards more crustally influenced compositions (see discussion about the role of the continental crust, below). Alkaline B1 lavas from Skien make up an anomaly, with HIMU like initial Nd and Sr signatures (Fig. 8, data from Anthony et al.1989).

It is important to notice that even the most ”crust-like” among the intrusive rocks, such as the Drammen and Finnemarka biotite granites show Sr and Nd isotopic signatures indicating a mainly mantle derived origin of the granitic magmas (Trønnes and Brandon 1992). Lu-Hf data from zircons confirm this, although also demonstrate that Mesoproterozoic crustal components have had an influence (Haug 2007).

Volume estimates from geophysics and petrological modelling

The large fraction of intermediate to felsic lavas and intrusive rocks at the present level of erosion is a striking feature of the Oslo Rift, and somewhat of a petrological anomaly (Table 2). To account for the observed volumes of evolved igneous rocks by magmatic differentiation of mantle-derived parent magmas, at least 65 000 km^3 of hidden mafic-ultramafic cumulates are neccessary (Table 2; Neumann 1980, 1994, Neumann et al. 2004). The presence of a regional, positive gravity anomaly overlapping with the Oslo Graben (Ramberg 1976) has been interpreted as evidence of the necessary volumes of high-density cumulates in the deep crust (Fig. 9a), which are required by the currently accepted petrogenetic models for the rift magmatism (Neumann 1980, Neumann et al. 2004).

In a reinterpretation of gravity and seismic data from the Oslo Graben and surrounding areas, Ebbing et al. (2005) concluded that the regional postive gravity anomaly discovered by Ramberg (1976) is a result of a combination of crustal thinning under the rift and the presence of dense, Precambrian high-grade metamorphic rocks at depth (Fig. 9b). In their interpretation, there is no evidence for the presence of a mafic-ultramafic body in the lower crust under the Oslo Graben, and unexposed mafic rocks must be situated at shallow crustal levels, immediately below and closely associated with the felsic to intermediated rocks exposed at the present-day surface. If such a geometry can accomodate the volumes of cumulates required to produce the felsic and intermediate magmatic rocks in the Oslo Graben by fractional crystallization of a mafic parent magma seems highly questionable. The consequences of this new interpretation of geophysical data for the understanding of the petrology of intermediate and felsic rocks have yet to be worked out. It should be noted that a *crustal* source for larvikite and associated rocks is contradicted by radiogenic isotope data (Fig. 7).

Table 2 Volume estimates of Permo-Carboniferous magmatic rocks in the Oslo and Skagerrak grabens

	Total volume (km^3)	Basaltic rocks	Intermediate rocks	Syenitic-granitic rocks
Oslo Graben				
Rift stage 1	~500	100 %		
Rift stage 2RP lava	~2000		100 %	
Larvik larvikite	~10000			100 %
Rift stage 3	~ 500	~ 20%	~ 40%	~ 40%
Rift stage 4 syenites-granites	~14000			100 %
Observed	~ 28 000	~ 6%	~ 44%	~50%
Eroded	25 000-30 000??			
Deep- seated	> 65 000	100 %		
Skagerrak Graben	~ 4000??	100 %	??	??
Shallow intrusives	??			
Deep-seated	> >65 000??			

From Neumann et al. (2004), estiamates on unexposed rocks based on data from Ramberg (1976)

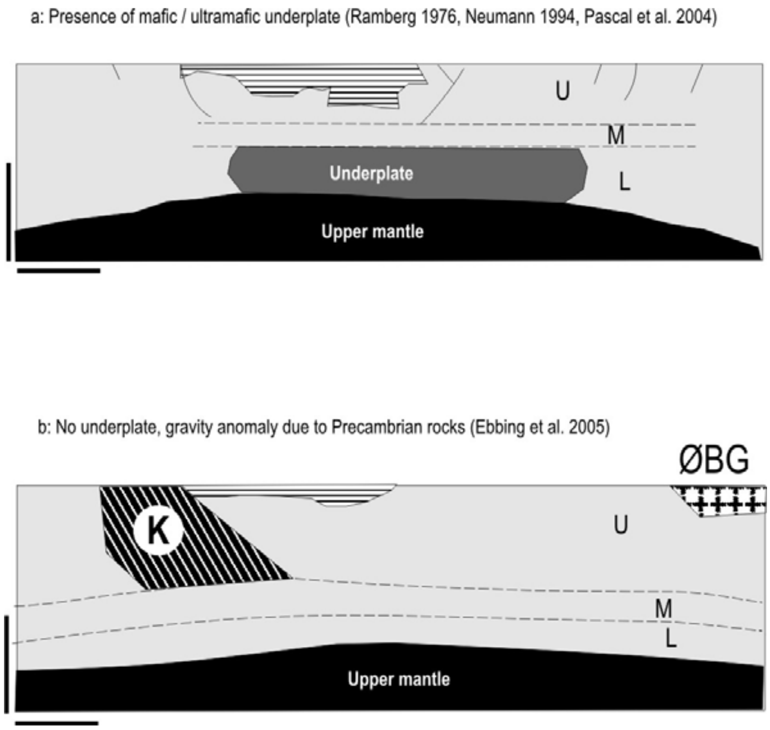


Fig. 9
Contrasting interpretation of crustal structure across the Oslo Rift. Note that the two profiles are not exactly coinceding, *a* is a transect WNW-ESE roughly at the latitude of Oslo, *b* strikes NW-SE across the southern part of the Oslo Fjord. Igneous and sedimentary rocks of the Oslo Rift are shown by horizontal ruling, the dense, diagonally ruled field in *b* (marked K) represents Precambrian rocks of the Kongsberg complex (mafic to tonalitic gneisses, amphibolites, granulites). ØBG is part of the ca. 925 Ma Østfold-Båhus batholith, which also plays a part in the rift evolution model of Slagstad (2006). U, M, L: Upper, middle and lower continental crust, respectively. Length of horizontal and vertical scale bars: ca. 20 km. The sections have been simplified from *a:* Pascal et al. (2004) and *b:* Ebbing et al. (2005).

Rifting of a differentiated continent – multicomponent crustal contamination.

It has generally been assumed that Precambrian stuctures have played a significant role for the evolution of the Oslo Rift (Sundvoll and Larsen 1994). However, as seen in Fig. 10, the Oslo Graben crosscuts the major Precambrian shear zones in southwestern Fennoscandia. The position of Oslo Rift roughly coincedes with a rapid, ≥ 55 km increase in lithospheric thickness from west to east, which is thought to be an important control on the development of the rift (Pascal et al. 2004). Recently, Slagstad (2006) has suggested that lithospheric weakening due to the presence of heat-producing late Sveconorwegian granites in the middle crust controlled the location of rifting. However, the granitic intrusions invoked in the model were probably situated at a shallower level in the crust at the time of rifting than assumed in the model (Fig. 9b), and too shallow for the mechanism to be effective.

The intemediate to felsic igneous rocks of the Oslo Graben show Sr, Nd and Pb, isotope ratios indicating a dominating influence of mantle-derived components to the source of magmas (Neumann et al.1988, Trønnes and Brandon 1992). However, most of the syenitic and alkali granitic intrusions studied show trends towards lower ε_{Nd} and somewhat elevated $^{87}Sr/^{86}Sr$, indicating minor crustal contamination (Fig. 8). Some attempts to model the influence of crustal contamination on the isotope and trace element composition of the evolved magmatic rocks have invoked a ”LILE-depleted lower crustal component” based on data from the late Mesoproterozoic granulite facies gneisses of Tromøy and neighbouring islands in southernmost Norway, which were thought to represent a deep Fennoscandian continental crust. However, the mafic to tonalitic granulite-facies gneisses of Tromøy island have been shown to be part of a low-K calc-alkaline (s.l.) island arc fragment accreted onto the Fennoscandian shield in the late Mesoproterozoic, and their low-LILE geochemsitry reflects the primary signature of the protolith, and not depletion of LILE during high-grade metamorphism (Knudsen and Andersen, 1999). This rock complex is thus highly anomalous in a Fennoscandian sense, and is a questionable choice as an endmember in contamination modelling.

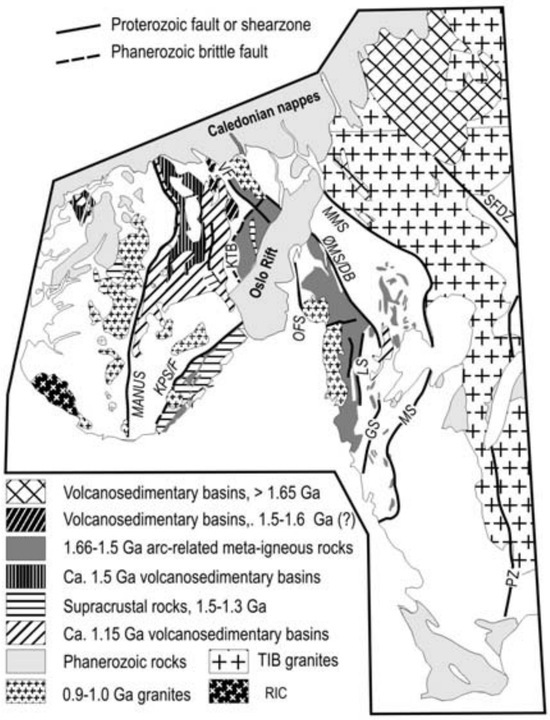


Fig. 10
A simplified map of the Precambrian rocks of SW Fennoscandia. Abbreviations: MANUS: Mandal-Ustaoset lineament, KPS/F: Kristiansand-Porsgrunn shear zone and brittle fault, KTB: ”Kongsberg-Telemark boundary”. VF: Vardefjell shear zone, OFS: Oslo Fjord shear zone LS: Lerdal shear zone, ØMS/DB: Ørje mylonite zone / Dalsland boundary fault, GS: Göta Älv shear zone: MS: Mylonite zone, PZ: Protogine zone. SFDZ: Sveconorwegian frontal deformation zone. TIB: Paleoproterozoic Transscandinavian Igneous Belt (granites), RIC: Rogaland Intrusive Complex (ca. 930 Ma anorthosite and associated rocks).

Based on a comprehensive database of trace element and isotope data from the rocks of southwestern Fennoscandia and a realistic model of crustal architecture (Fig. 11), Andersen and Knudsen (2000) deduced a group of crustal components which are applicable as contaminants in the rift-related magmas.

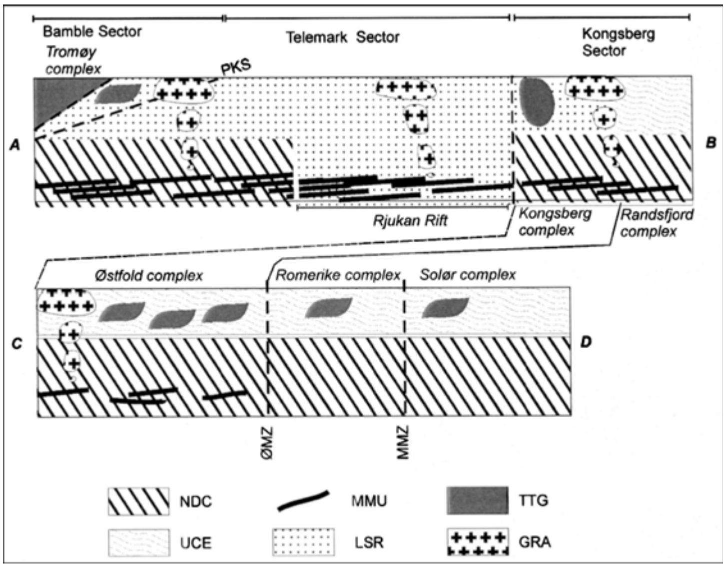


Fig 11
Crustal architecture along the west (upper) and eastern (lower) flanks of the rift, from Andersen and Knudsen (2000). Component acronyms: NDC: ”Normal deep crust” MMU: Mantle-derived mafic underplate, TTG: Mesoproterozoic calcalkaline gneisses, UCE: Eastern type upper continental crust. LSR: ”Low Strontium Crust” of the Telemark block, GRA: Late Mesoproterozoic granites.

Contrary to what has been suggested in earlier studies of Precambrian geochemistry in the region, neither Andersen and Knudsen (2000) or Andersen et al. (2001, 2004b, 2007) have found geochemical evidence for the presence of a clearly LILE depleted lower continental crust in the region. Rather, a relatively uniform ”average continental crust” component seems representative of the bulk of the lower crust in the region. This is, however, supplemented by basaltic underplate (”MMU”) and by Precambrian calcalkaline rocks (”TTG” in Fig. 11 and 12). Late Sveconorwegian granite is widely distributed in the upper crust on both sides of the rift.

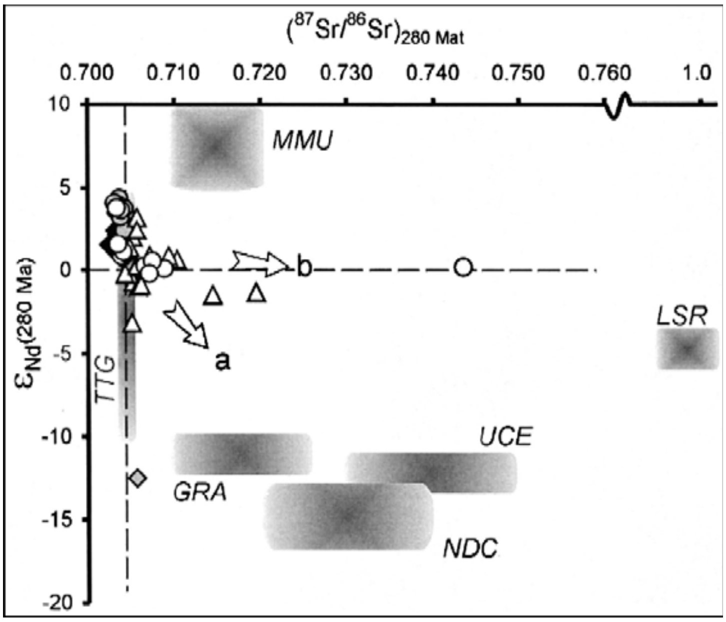


Fig 12
Crustal endmembers and possible contamination-trends in igneous rocks from the Oslo Graben. Note that the near-vertical trend seen in larvikites, rhomb porphyries and some syenites is compatible with contamination by Mesoproterozoic calc-alkaline gneisses found along the western flank of the graben (e.g. Kongsberg complex). Such trends are commonly attributed to contamination with LILE depleted rocks supposed to reside in the lower continental crust (e.g. Neumann et al. 2004).

The almost vertical array in the epsilon Nd vs. initial $^{87}Sr/^{86}Sr$ diagram observed in larvikite and related rocks (Fig. 8 and 12) is compatible with contamination with Precambrian calcalkaline rocks (the ”TTG” component of Andersen and Knudsen2000) corresponding to the Mesoproterozoic gneisses of the Kongsberg-Marstrand Block of southwestern Fennoscandia (Andersen 2005). In the model of Ebbing et al. (2005), such rocks make up a significant fraction of the lower to middle crust along the southwestern flank of the Oslo Graben (Fig. 9b). The syenitic and granitic rocks plot along a different contamination trend towards components that are moderately enriched in LILE. Some evidence suggests that the very characteristic low-Sr crust of the Telemark block, characterized by extremely radiogenic $^{87}Sr/^{86}Sr$ and $\leq$ 50 ppm Sr may have made minor contributions to some of the granites.

Part 2: Excursion guide

Day 1: Saturday, August 2nd, 2008

General features of the Oslo Graben, basement, sedimentary rocks and lavas.

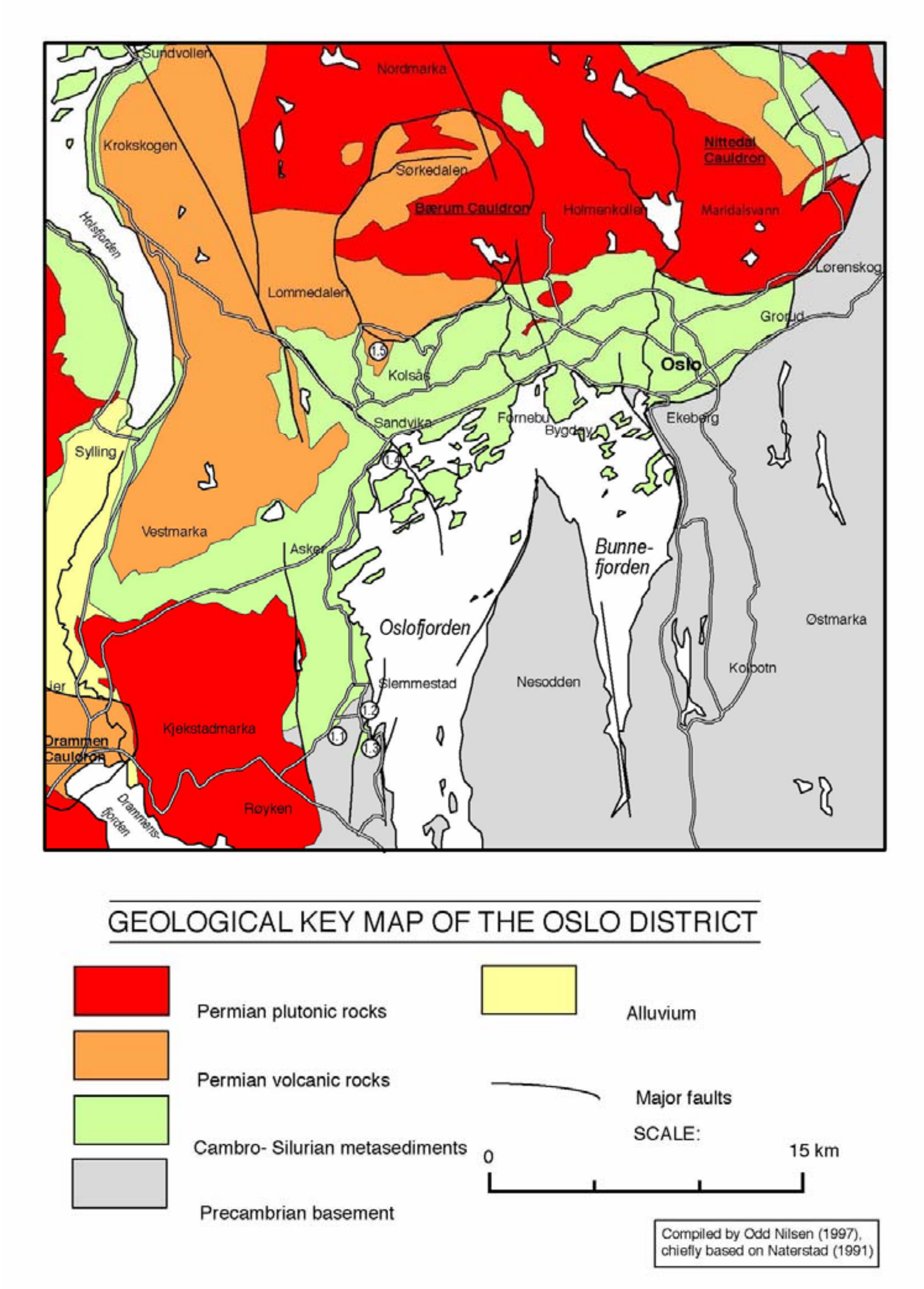


Fig.13
Simplified geological map of the area around Oslo
Grey: Precambrian basement
Green: Early Paleozoic (Cambrian-Silurian) sedimentary rocks
Brown: Permian lavas (basalt and rhomb porphyry)
Red: Permian intrusions (granite and syenite)

Locality 1.1: *The Cambrian basal conglomerate, Bødalen, Slemmestad*
Coordinates[2]: 0582146 6625382

At the playground we can study the sub-Cambrian peneplain, marked by a patchy cover of Cambrian conglomerate on a weathered Proterozoic gneissic basement. Within the basal sediments are Middle Cambrian fossils, e.g. the primitive annelid *Volborthella* (Yochelson et al. 1977) indicating the time of transgression of the Cambrian sea from north towards the south.

The Oslofjorden area reveals a system of small-scale basin-and-range like structures, tilted fault blocks etc. Generally the N-S trending faults west of the Oslofjord make an antithetic fault pattern relative to the larger west-facing Oslofjorden Master Fault to the east. Each of the east-facing faults having dip slip throw of about 100-200 m. The fault scarp at Nesodden (the Oslofjorden Master Fault) has a throw of 1km (Fig. 14).

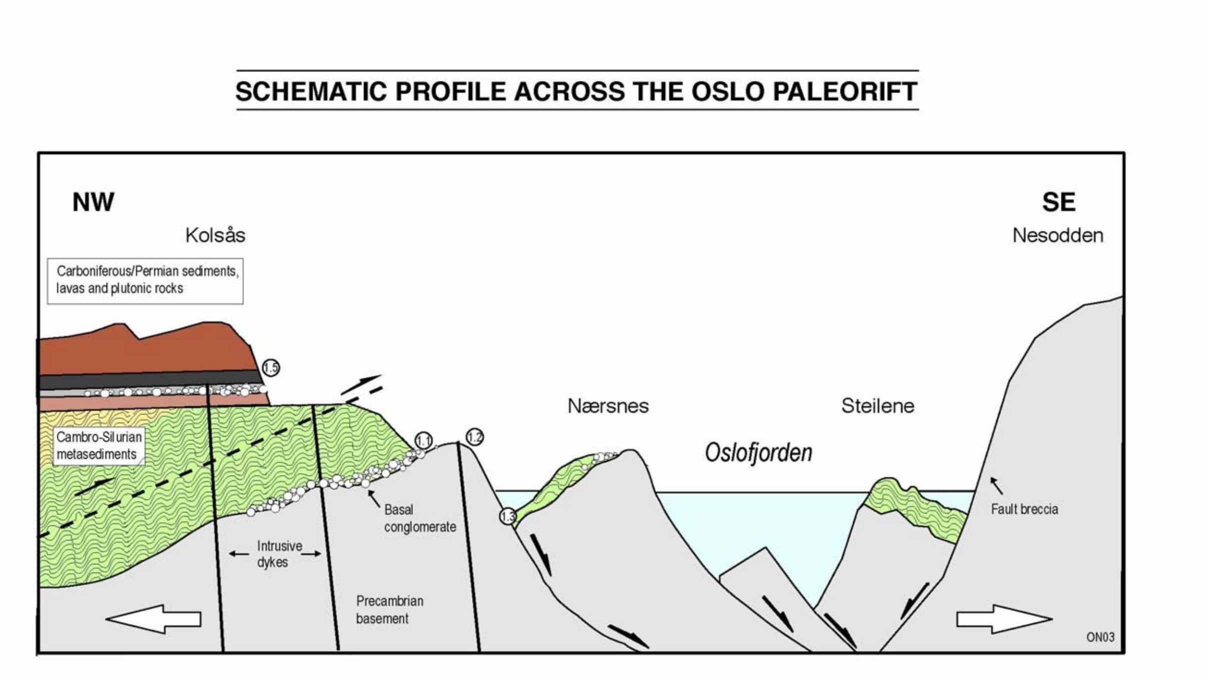


Fig. 14
Schematic profile across the Oslo Rift south of Oslo, with the tectonic setting of localities 1.1 to 1.5

[2] Coordinates given in this excursion guide are UTM coordinates in zone 32V, map datum WGS84. All positions have been measured in the field.

Locality 1.2: *The basement. Roadcut at Morberg, Slemmestad*
Coordinates: 0583695 6626779

The bedrock geology of the Precambrian areas on both sides of the Oslo Fjord (Østfold-Røyken-Kongsberg) consists of a series of orthogneisses of calcalkaline composition whose protoliths were formed along a long-lived, Mesoproterozoic cordilliera-type continental margin. Most of the rocks are very strongly deformed, but in some cases, the nature of the protolith can nevertheless be identified. The roadcuts at Slemmestad show two very characteristic rock types: A fine-grained metarhyolite with well-preserved ignimbritic structures, which is crosscut by white, medium-grained, muscovite-bearing granite. With an age of 1615±31 Ma (Fig. 15), the metaignimbrite is the oldest rock in the region so far dated by U-Pb. The granite at this locality has not yet been dated, but similar types of granite from the east side of the Oslo Fjord give ages around 1520 Ma. Lu-Hf isotope data from zircons in the metarhyolite suggest a clear influence from older rocks of the Fennoscandian shield, most probably late Paleoproterozoic granites belonging the Transscandinavian Igneous Belt (TIB), which probably make up the depositional basement for the arc volcanics.

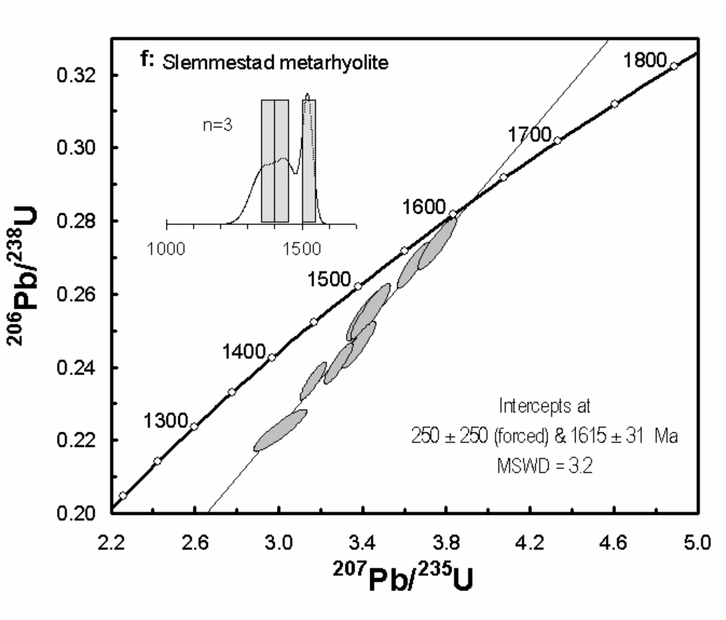


Fig. 15
LAM-ICPMS U-Pb data for zircons separated from the Slemmestad metarhyolite (Andersen et al. 2004b).

A N-S trending Permian diabase dike intersect the gneiss/granite complex, and has been followed for more than 4 km. It is composed by plagioclase, brown hornblende and magnetite, with minor biotite and apatite.

Locality 1.3: *The basal contact of the early Paleozoic sediments, Nærsnes*
Coordinates: 0584195 6625737

Close to the chapel at Nærses (Fig. 14), an outcrop of the Middle Cambrian Alum Shale Formation is exposed. The lithology is organic-rich, black shale with concretions of dark, bituminous limestones ("stinkstones"): Sulphides are abundant as disseminations and concretions within the shales and limestones (Oftedahl,1955) which contain a high content of uranium. As an average, the alum shales of the Cambro-Silurian succession in the Oslo Region contain 87 ppm U, 49 ppm Mo, and 2000 ppm V (Dypvik,1984).

Mænaite occurs as a sill on the northern side of the road adjacent to the Nærsnes chapel. Mænaite is a plagioclase-bearing bostonite, i.e. a microsyenite dike rock and the present mænaite contains chiefly turbid plagioclase and minor intergranular chlorite-pseudomorphoses after hornblende and/or pyroxene. Accessory constituents comprise zircon, apatite, carbonate, pyrite and sphene. The mænaites constitute the earliest magmatic phase in the Oslo Palaeorift with ages 304- 294 Ma (Sundvoll et al. 1992) and occur mainly as sills.

Following the road towards the bend to the west we approach a N-S trending, E-facing normal fault which separates the Precambrian basement from the downfaulted and deformed Cambro-Silurian block in the east. The fault shows clear indications of repeated brittle brecciation - a common feature along many of the Oslo Graben faults. The fault plane dips about 40^{o} to the east. Striations on the fault plane clearly indicate a dip slip normal fault.

Locality 1.4: *Kalvøya*
Coordinates: 0585756 6639757

The island of Kalvøya (Fig. 16) consists of an anticline with upper Middle Ordovician (Caradoc) sediments (Nakholmen and Solvang Fm. (Stage 4b)) in the core and Upper Ordovician (Ashgill) sediments on the flanks (i.e. the Venstøp, Grimsøya, Skjerholmen, Skogerholmen, Husbergøya and Langøyene Formations). The Langøyene Formation was formerly called Stage 5b, ending the Ordovician stratigraphy in the Oslo Region (Owen et al. 1990, Naterstad et al. 1990, Larsen et al. 1992, Bockelie 1996)

The Ordovician sediments consists of fossiliferous nodular limestones, siltstones and shales. The sequence represents two regressive phases: The first ending with the Middle Ordovician (Solvang Formation), the second ending with the Upper Ordovician (Langøyene Formation). During the Upper Ordovician there was an increase in influx of coarse clastic components, terminating in the deposition of oolitic sandstone (Langøyene Formation). On the NW side of the island is a 1 m thick intraformational conglomerate bed belonging to the same formation. The conglomerate was formed in a shallow marine environment, probably associated with tidal channels and microtectonic activity. A variety of lithofacies associations are recognized in the uppermost Ordovician of the Oslo-Asker district, suggesting intertidal to open marine depositional

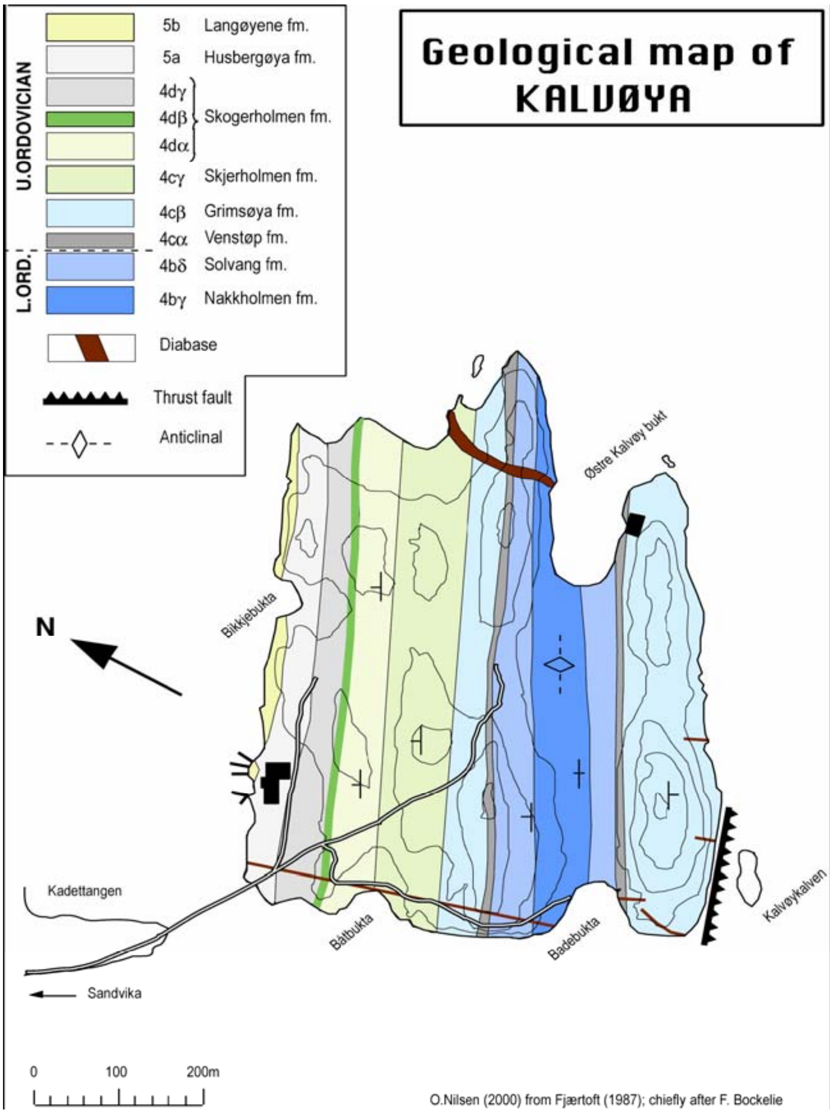


Fig. 16
Geological map of Kalvøya island

environments. The diverse fauna and the presence of local bioherms and reef-structures suggest subtropical to temperate environments.

The sediments just adjacent to the footpath bridge comprise shales and nodular limestones of the Husbergøya Formation. They dip about 50^{o} towards NW are cut by several N-S-striking Permian diabase dikes with chilled margins, partly with vesicular developments. Glacial striations are common on the eroded surfaces.

Locality 1.5: *The Ringerike sandstone, Asker Group and Permian volcanic rocks, Kolsås.*
Coordinates: 0585756 6639757

The ascent of Mt. Kolsås (Fig. 17) is one of the classical profiles in the geology of the Oslo Rift. The ascent starts in upper Silurian sandstones (*Ringerike sandstone*). The sandstone has been tilted, and is cut through by an erosional surface (the sub-Permian peneplain) prior to deposition of the Asker Group. At Kolsås, the Asker group (Fig. 18) is represented by the *Kolsås Formation* (mudstones and shales), which is overlain by the *Tanum Formation* quartz conglomerate. The uppermost formation (the volcaniclastic *Skaugum Formation*) is missing.

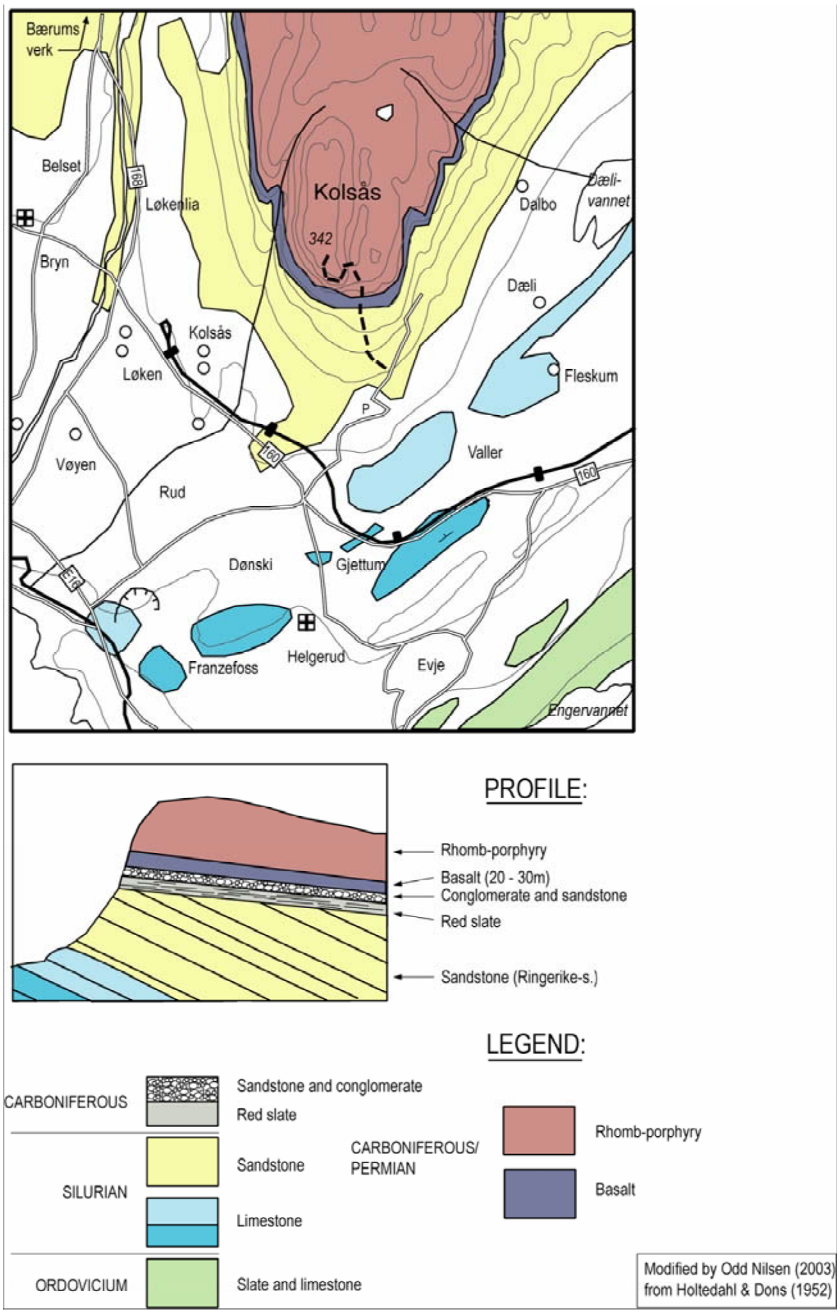


Fig. 17
Geological map and profile of the Kolsås area.

The sedimentary rocks are covered by a ca. 20 m thick basalt belonging to the B1 lavas. The basalt at Kolsås is a tholeiite, which shows geochemical evidence of having suffered crustal contamination.

The upper part of the Kolsås cliffs are formed by the lowermost rhomb porphyry lava (RP1), with a very characteristic phenocryst morphology (Fig. 19). Rhomb porphyries are lavas of latitic composition distinguished by the presence of large, generally rhomb-shaped anorthoclase feldspars phenocrysts. Some flow units can attain surprising thicknesses (several 10s of metres). The abundant presence of scoriaceous and vesicular lava tops and the occational flow structure within the flows show that we are dealing with lavas and not, for example, ignimbrites.

Fresh rhomb porphyry is typically medium gray in colour. At Kolsås, the lava has a very characteristic brown colour due to postmagmatic alteration. Vug fillings with calcite, agate and zeolites (laumontite) suggest that the rocks have suffered some very-low-grade metamorphsim.

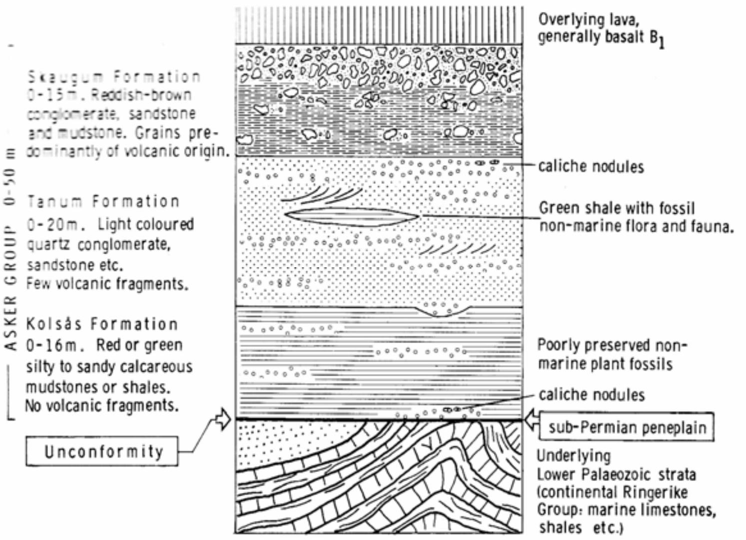


Fig. 18
Schematic cross section through the upper Carboniferous Asker Group (Henningsmoen 1978). For a more detailed stratigraphic column, see Larsen et al. (2008).

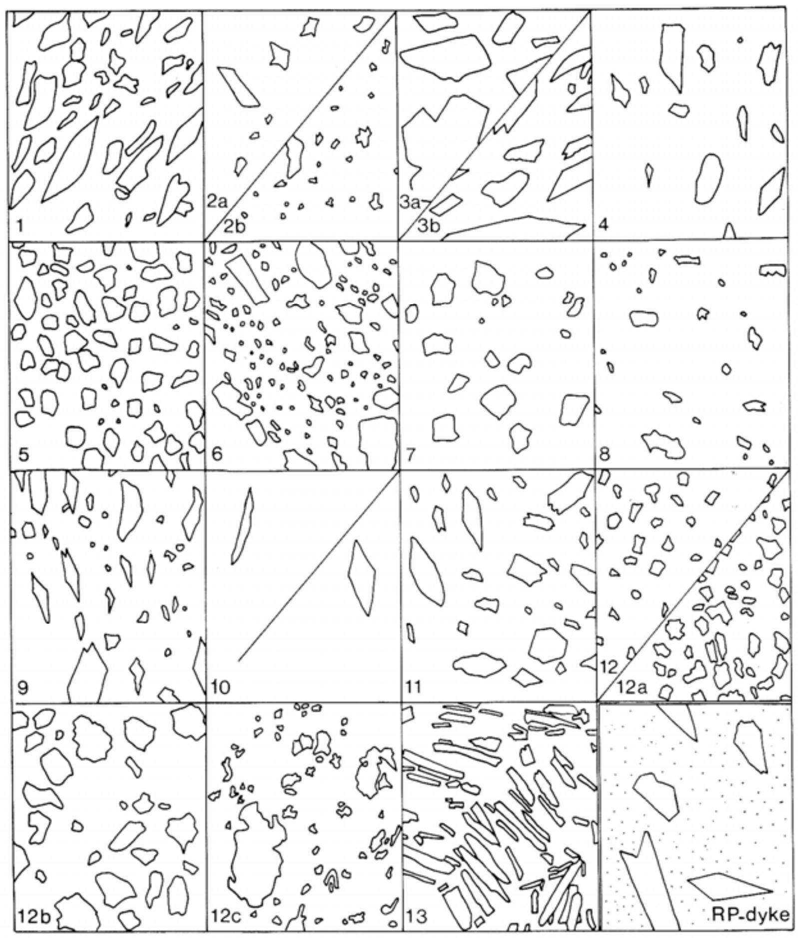


Fig 19
Rhomb porphyry identification chart. From Larsen (1978), based on Oftedahl (1952). Identification and mapping of rhomb porphyry lavas is one of the more exotic skills traditionally thought in undergraduate fieldcourses at the University of Oslo.

Day 2: Sunday, August 3rd, 2008

The Drammen and Finnemarka biotite granites
(Largely from Trønnes and Brandon 1992)

The Drammen batholith intrudes Precambrian gneisses to the east and Cambro-Silurian sedimentary rocks to the north, west and south. Permian extrusives of the Glitrevann cauldron border the northwestern corner of the granite complex (Fig. 20). The emplacement of the granite batholith pre-dates the subsidence of the Drammen and Glitrevann cauldrons (Gaut 1981 and Stenstrop, pers. comm., 1991).

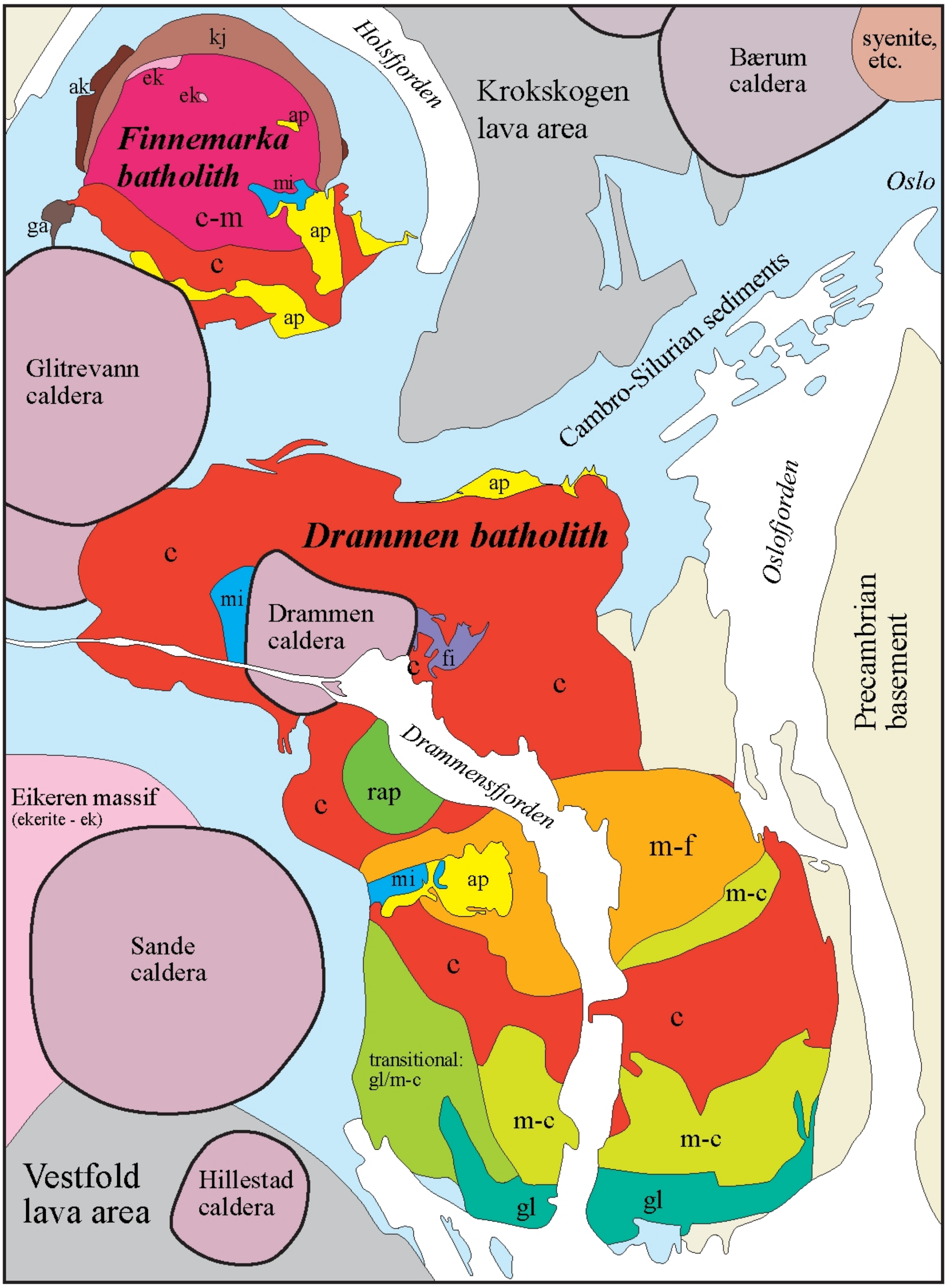
Gravimetric data indicate that the batholith is a relatively thin (about 3 km thick) tabular body with one or more root-like extensions in the eastern-central area (Ramberg 1976). Alternatively the data could be interpreted as a pseudo-cylindrical body grading downwards into a mixture of stoped blocks and intrusives. The gravimetric data also indicate that the granite continues beneath the Cambro-Silurian sediments at shallow level for about 3 km southwest of the Drammen cauldron and beneath the sedimentary rocks and gneisses for at least the same distance beyond the northeastern contact. A negative gravity anomaly along the Oslo Fjord is possibly related to a further 15-20 km subsurface extension of the batholith towards east and northeast. The calculated volume of the batholith without the latter extension is 1811 km^3 (Ramberg 1976).

Petrography

The spatial distribution of the main petrographic varieties are shown in Fig. 20. In addition to these rock types numerous aplite and pegmatite dikes, veins and irregular segregations are found throughout the area but are concentrated in the central part of the batholith. Post-magmatic explosion breccias transecting the granites are observed close to the southern margin of the Drammen cauldron in the coarse-grained granite type and 4 km to the southwest in the rapakivi granite.

Perthitic alkali feldspar, recording various stages of albite exsolution, is the dominant mineral in all of the granites, and small amounts of early crystallized plagioclase (oligoclase, An_{20}) grains are present in parts of the coarse-grained granite, especially in the northern area. Microcline is absent from all of the granite types. Evenly distributed Fe-oxide dust throughout most of the feldspar crystals give the rocks a distinctly red colour. Partly chloritized biotite is the most abundant mafic silicate, occurring in all of the petrographic types. The biotites are most remarkable for their high F-contents. Minor amounts of amphibole and epidote occur in the course-grained granite and the rapakivi granite, and small amounts of muscovite, fluorite, topaz, carbonate and pyrite are present locally, and in particular in the central part of the batholith. Fe-Ti-oxides, titanite, zircon, and apatite are widespread accessories.

The most widespread petrographic variety of the Drammen batholith is an equigranular ***coarse-grained granite*** (3-5 mm grain size) containing generally less than 3-5 vol% of early crystallized oligoclase in addition to the common mineralogy of quartz (30-35 vol%) and perthitic alkali feldspar (60-65%). The area west of the Drammen cauldron and a 0.5-2 km wide border zone along the northeastern margin, contains a variety with up to 5-10 vol% oligoclase. The oligoclase crystals have frequently undergone partial hydrothermal bleaching. Microscopically the late- to post-magmatic bleaching can be recognized by the precipitation of red iron oxide (hematite) along microcracks in feldspar crystals devoid of the otherwise evenly distributed Fe-oxide dust. Locally, the coarse-grained granite, and in particular the oligoclase-rich variety, contains up to 25% fine-grained interstitial groundmass.



Abbreviations
ga: gabbro
ak: akerite (qz. monzodiorite)
kj: kjelsåsite (qz. syenomozonite)
ek: ekerite (peralkaline granite)
c: coarse-grained granite
c-m: coarse- to medium-grained gr.
m-c: medium- to coarse-grained gr.
m-f: medium- to fine-grained gr.
ap: aplitic porhyry
mi: microcrystalline porphyry
fi: fine-grained porphyry
gl: glomeroporpyritic granite
rap: rapakivi granite

References:

Finnemarka complex:
Stenstrop (1989,
Ph.D. thesis, Univ. Aarhus)

Drammen complex:
Trønnes & Brandon (1992, Contr. Mineral. Petrol. 109, 275-294)

Fig.20
Geological map of the Drammen and Finnemarka batholiths (compiled by R.G. Trønnes)

A coarse-grained ***cumulophyric granite*** is confined to a 2 km wide zone along the southern margin of the batholith. Subhedral and somewhat rounded phenocrysts of perthitic feldspar, (8-15 mm) are incompletely surrounded by a interstitial medium-grained (3 mm) granitic matrix. This granite type has the highest content of the accessory minerals titanite, zircon and Fe-Ti-oxides. Gradual transitions into an equigranular ***medium- to coarse-grained granite*** occur futher northwards.

South of the Drammen cauldron the coarse-grained granite is transected by a sub-circular ***rapakivi granite*** pluton. Zoned feldspar ovoids (5-15 mm in diameter) comprising large perthitic cores and thin albitic rims are set in a fine-grained quartz-rich groundmass (0.5-1 mm). The feldspar ovoids constitute about 50% of the rock volume. The primary magmatic biotite is almost completely chloritized, and epidote and amphibole are quite widespread.

The central part of the Drammen batholith is dominated by a ***medium- to fine-grained granite***, characterized by a remarkably low content of mafic minerals. Muscovite and flourite are more conspicious than in the other rock types. With an average grain size varying from 1 to 3 mm, the granite shows gradual transitions into the aplitic porphyry in the same area.

Three petrographic varieties of quartz-feldspar porphyries are present in the batholith. A ***microcrystalline porphyry*** with 3-5 mm rounded phenocrysts of quartz (30%) and perthitic alkali feldspar (70%) occurs close to the western central margin of the batholith (Røysjø area) and along the western margin of the Drammen cauldron (Landfall area), respectively. Aggregates of ilmenorutile and topaz in a limited area are most likely of post-magmatic, hydrothermal origin. Directly east of the microcrystalline porphyry in the central part of the batholith is an area of mainly quartz-phyric and leucocratic ***aplite porphyry*** (1-3 mm phenocrysts in a 0.5 mm groundmass). A small body of aplitic porphyry is also present along the northern border of the batholith. The ***fine-grained porphyry*** east of the Drammen cauldron contains 5-15 mm phenocrysts of mainly perthitic alkali feldspar and minor quartz in a 1 mm groudmass.

Field relations and intrusive sequence

Most of the granite types within the batholith seem to represent separate intrusive phases. The contact relations, however, are often unclear with gradual transitions and sharp contacts occurring at different locations along the same border between two petrographic varieties. This may be a result of the intrusion of a new magma into an already emplaced, but only partially solidified magma. Where the solidification of the early intrusion is near completion, the boundary to the new intrusion may become sharp, but where the early intrusion is still mostly liquid a more extensive mixing and mutual assimilation may result in a transitional boundary. Partial remelting of contact portions of an early intrusive phase could also lead to transitional or ambiguous contact relations. In addition to the nature of the contacts on an outcrop scale, the topographic relations between intruded roof massifs and underlying intrusions have proven useful for the establishment of the internal intrusive sequence of the Drammen batholith.

The coarse-grained, the medium- to coarse-grained and the cumulophyric granites seem to represent the earliest intrusives of the presently exposed section of the batholith. The transitions between these varieties are mostly gradational, and they may be parts of the same intrusive event. The microcrystalline porphyries (especially in the central part of the batholith) are chemically similar to, and may be genetically related to, the coarse-grained granite. The intrusions of all of the porphyries as well as rapakivi and the medium- to fine-grained granite, however, appear to succed the intrusion of the coarse-grained granite. In particular the fine-grained porphyry and the aplite porphyry show clear intrusive relations to this rock type.

The aplite porphyry and the medium- to fine-grained granite may be parts of the same, final intrusive phase. The porphyry is generally confined to the topographically highest areas west of the Drammen Fjord, and it may represent relatively late stage crystallization of the magma, consistant with a viscosity increase resulting from a drop in the partial pressure of volatiles (mainly H_2O). It is also possible that the aplite porphyry intruded the medium- to fine-grained granite. Limited areas (10-100 m dimensions) of the latter type within the aplite porphyry may represent large xenolithic rafts.

The Finnemarka batholith

The internal intrusive relations within the southern part of the Finnemarka complex appears to be similar to those in the Drammen batholith (Stenstrop 1989) and the central biotite granitic stock of the Glitrevann cauldron (Gaut 1981; Jensen 1985). Aphanitic to microcrystalline porphyries seem to be earlier than or approximately contemporaneous with volumetrically dominant coarse- to medium-grained granites, with final intrusive phases consisting of aplitic granites. The BG2 of the northern part of the central granitic area of the Finnemarka complex, is rimmed by quartz monzodiorite (akerite) and quartz syenomonzonite (kjelsåsite), and a small gabbro intrusion immediatetly west of the complex may also belong to the Finnemarka magmatic series. Within the coarse- to medium-grained BG2 granite there are also small areas with peralkaline granite (ekerite).

The batholith is clearly cut by ring faults and dikes of the Glitrevann cauldron (Gaut 1981). Ramberg (1976) concluded that the intrusion is cone shaped, extending to a maximum depth of about 7.5 km, and he estimated the volume to be 336 km^3. The Finnemarka batholith may therefore have a slightly larger average thickness (3.4 km) than the Drammen batholith (2.8 km).

Hydrothermal alteration and mineralization

Ihlen et al. (1982) and Ihlen and Martinsen (1986) described the late- to post-magmatic alteration and mineralization phenomena associated with the Drammen granite, and Olsen and Griffin (1984 a, b) presented fluid inclusion data. In addition to simple exsolution of the perthitic feldspars and the hydrothermal bleaching of the early oligoclase, especially in the northern part of the batholith, the most widespread and pervasive postmagmatic alteration is albitization, mostly affecting the medium- to fine-grained granite in the central part of the batholith. The albitization seems to be closely associated with the exsolution of the perthitic alkali feldspar, and involves additional replacement of red, K-rich domains (finely dispersed Fe-oxide dust) by white (clean) albite. Extensively albitized granite areas appear bleached, and can extend over distances of less than one meter to a few hundred meters. Although bleached samples were avoided in the study by Trønnes and Brandon (1992), the whole rock chemistry indicates that the analysed samples of medium- to fine-grained granite and the aplite porphyry have undergone some late- and/or post-magmatic Na-enrichment. The high F-content in most of the Drammen granite samples, and especially in the medium- to fine-grained granite, indicate that the elevated Na/K-ratios may also partly be caused by the displacement of minimum melt compositions towards the albite component (e.g. Manning 1981). Miarolitic cavities and small quartz±fluorite veins are relatively widespread within the cumuloporphyritic granite along the southern margin of the Drammen batholith.

Other hydrothermal alterations and mineralizations also occur most frequently in the central area of the batholith. These include quartz-sericite-pyrite ±topaz, sericite-chlorite, and kaolinite alterations, as well as common Mo- and rare W-mineralizations (Ihlen et al. 1982).

Petrogenesis

The eight separate petrographic types of the Drammen batholith range in SiO_2 from 70 to 79 wt% and have experienced variable amounts of fractionation of feldspars, biotite, zircon, apatite, titanite and Fe-Ti-oxides. The initial Sr, Nd and Pb isotopic ratios and a decoupling between the variations in the SiO_2 content and the aluminum saturation index [ASI=Al_2O_3/(CaO+Na_2O+ K_2O)] show that the various intrusive phases are not strictly comagmatic.

The ε_{Nd} values of the southern part of Finnemarka (+3.5 to +4) and the northern part of the Drammen granite (+1 to +1.5) are high and indicate insignificant (for Finnemarka) to minor Precambrian crustal or enriched mantle contributions. The very low ε_{Sr} values of all of these samples (-1 to -12, outside the main Oslo Rift magmatic array, Neumann et al., 1988; Anthony et al., 1989), point to a time integrated Rb-depleted crustal contaminant or an EM1 mantle component. The earliest extruded alkali basalts along the southwestern margin of the Oslo Rift are the only other samples within this low ε_{Sr} area, but their isotopic signature may also be linked to a mantle enrichment event (involving an EM1 component), e.g. associated with the Fen carbonatite magmatism 540 Ma ago. For a given $^{206}Pb/^{204}Pb$, the $^{208}Pb/^{204}Pb$ ratios of the Drammen and Finnemarka batholiths are distinctly lower than those of the Skien alkaline volcanics and all other magmatic Oslo Rift rocks. This may indicate that the lithosphere of the central part of the rift had a time integrated Th-depletion.

The samples from the southern part of the Drammen batholith, characterized by the presence of abundant miarolitic cavities, have ε_{Nd} near 0 (-0.7 to +0.4) but strongly elevated ε_{Sr} of +35 to +67. The combined Pb isotopic ratios of all the samples analyzed indicate that the Precambrian crustal anatectic contribution is in the form of time integrated Th- and U-depleted lower crust, and the high ε_{Sr} of the southern part of the Drammen granite results from shallow level wallrock assimilation or magma-fluid interactions. The remarkably low contribution of old crustal components to the Finnemarka and the northernmost Drammen batholiths may result from extensive late Precambrian intracustal differentiation in southwestern Scandinavia, leading to widespread upper crustal granites (~900 Ma) and a correspondingly dense and refractory lower crust, in particular in a zone intersecting the central part of the rift (see e.g. Killeen and Heier, 1975).

Liquidus phase relations and mass-balance constraints permit derivation of the granites from mildly alkaline to tholeiitic melts by extensive crystal fractionation of clinopyroxene- and amphibole-rich assemblages. It is equally possible to form the granitic magmas by partial melting of Permian gabbroic crust. The peraluminous chemistry could be aquired by fractionation (in the form of partial melt separation from the solid residue and/or fractional crystallization) of low-ASI minerals like clinopyroxene and amphibole (Zen 1986). Either scenario is consistent with the isotopic constraints and with the presence of dense cumulates and/or residues in the lower crust. The lack of igneous rocks of intermediate composition associated with the Drammen and Finnemarka batholiths point to an efficient upper crustal density filtering. Considerable amounts of heat would be accumulated in this region if differentiated, intermediate melts could not escape to shallower levels. Successive magma injections would therefore easily result in anatexis (water-undersaturated dehydration melting) of already solidified mafic to intermediate melts and cumulates.

In spite of their largely peraluminous nature the biotite granites have certain characteristics in common with A-type and within-plate granites, in particular in the form of high contents of F, Nb and Y and hypersolvus feldspars. The major and trace element chemical variation within the Drammen granite suite indicate that the different rock types underwent additional and variable fractionation of plagioclase, alkali feldspar, mica, and accessory phases.

Locality 2.1: *Contact metamorphism at Lierskogen*

Coordinates: 0572005 6631249

The contact aureoles around the plutons of the Oslo Rift was the first place where the mineral reactions in sedimentary rocks during contact metamorphism at low pressure were first systematically studied (Goldschmidt 1911). Shales and limestones of lower Paleozoic age were heated to temperatures of 600-700 ^{o}C near the contact to the large, granitic intrusions. Whereas pure limestones recrystallized to marble, silicate-bearing sedimentary rocks formed hornfelses consisting of the minerals andalusite, cordierite, anorthite, orthopyroxene, diopside, grossular and wollastonite. By applying chemographic and thermodynamic principles, Goldschmidt (1911) could show that the mineralogy of the metamorphic rocks is a function of protolith composition only (temperature and pressure being approximately constant), and only ten equilibrium mineral assemblages are possible (the ten hornfels classes). This can be conveniently illustrated in a CaO-FeO-Al_2O_3 diagram (Fig. 21).

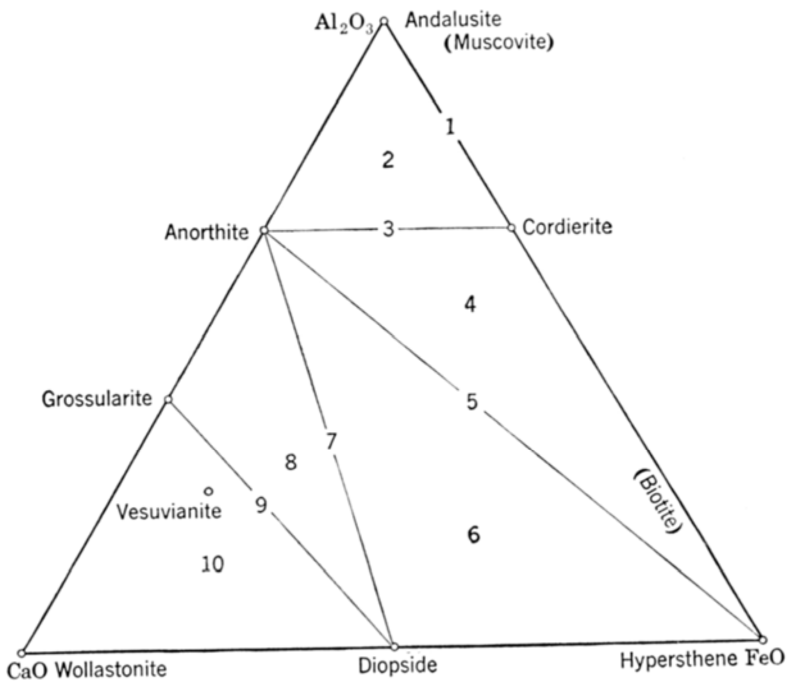


Fig. 21
The 10 hornfels classes of Goldschmidt (1911). This version of the diagram is taken from Barth (1962). Other phases to appear are quartz, orthoclase and accessory minerals (apatite etc.).

Locality 2.2: *Intraplutonic molybdenite mineralization, Sørumsåsen*

Coordinates: 573296 6625622

The Sørumsåsen deposit (Ihlen and Vokes 1978) is an intramagmatic deposit carrying molybdenite and minor scheelite in a system of quartz veins. The deposit was worked by the German occupants during the 2nd World War, and as a result of the abrupt end of operation in 1945, dumps of relatively high-grade ore are still present near some of the pits. The veins can be traced within a ca. 200 m by 800 m zone at the surface, and drilling has revealed that the mineralization continues at least to 100 m below surface. The mineralization is associated with clay alteration of the granite. The host rock is a coarse-grained variety of biotite granite (see locality 2.3), but the mineralization is spatially associated with dikes and irregular bodies of aplite and quartz-porphyry within the granite.

Locality 2.3: Coarse-grained granite
Coordinates: 0574235 6617722

The most widespread petrographic variety of the Drammen batholith is an equigranular *coarse-grained granite* (3-5 mm grain size) containing generally less than 3-5 volume % of early crystallized oligoclase in addition to the common mineralogy of quartz (30-35 volume %) and perthitic alkali feldspar (66-65 volume %). The area west of the Drammen cauldron and a 0.5-2 km wide border zone along the northeastern margin, contains a variety with up to 5-10 vol. % oligoclase. The oligoclase crystals have frequently undergone partial hydrothermal bleaching. Microscopically the late- to post-magmatic bleaching can be recognized by the precipitation of red iron oxide (hematite) along microcracks in feldspar crystals devoid of the otherwise evenly distributed Fe-oxide dust. Locally, the coarsegrained granite, and in particular the oligoclase-rich variety, contains up to 25% fine-grained interstitial groundmass.

Locality 2.4: Rapakivi variety
Coordinates: 0571210 6620538

South of the Drammen cauldron the coarse-grained granite is transected by a sub-circular *rapakivi granite* pluton. Zoned feldspar ovoids (5-15 mm in diameter) comprising large perthitic cores and thin albitic rims are set in a fine-grained quartz-rich groundmass (0.5 to 1 mm). The feldspar ovoids constitute about 50% of the rock volume. The primary magmatic biotite is almost completely chloritized, and epidote and amphibole are quite widespread.

The presence of the Drammen and Finnemarka biotite granites in the central part of the rift may reflect special features of crustal structure, which have counteracted deep crustal density filtering, thought to be important for other felsic and intermediate magmas in the rift. These intrusions lie on a straight line through the late Mesoproterozoic Østfold-Marstrand and Flå A-type granites, but a direct genetic connection to such source materials is contradicted both by the data of Trønnes and Brandon (1992) and by Lu-Hf isotope data of Haug (2007), both of which indicate a mainly mantle-derived origin for the biotite granite.

Locality 2.5: *Konnerud Pb-Zn-Cu skarn deposit*
Coordinates: 0563030 6622152

The deposit at Konnerud (Fig. 22) was mined intermittently from the 17th century until 1913. Like many of the Oslo Region contact deposits, the ore must have been small in tonnage, but locally very rich. One of the most interesting features of the Konnerud deposit is the well-deveoloped structural control on mineralization. The deposits are situated along the limiting faults of a small graben, such that mineralization is only developed in the footwall shales and limestones, the downfaulted block of upper Silurian sandstones is totally barren.

We will visit minedumps where the ordinary sulphide minerals of the deposit: Sphalerite, chalcopyrite, pyrite, bornite and secondary minerals formed from these can be found. Well-developed andradite is abundant, as are fluorite and calcite veins.

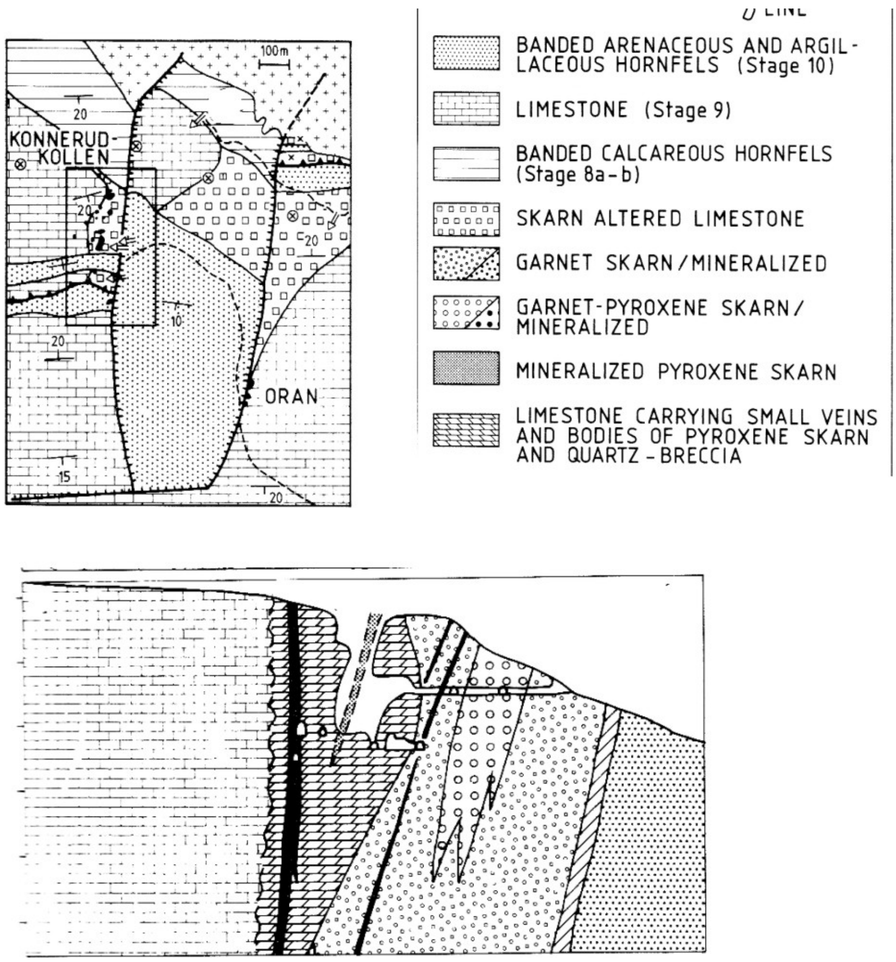


Fig. 22
Geological map and east-west cross-section of the Konnerud mining district, showing the structural and lithological controls on the distribution of mineralization. Cross section from Olerud and Ihlen (1986).

Other rocks of the northern Vestfold Graben

Locality 2.6: *The Eikeren alkali granite pluton*
Coordinates: 0555313 6612263

The "ekerite" or alkali granite of the Eikeren pluton is mildly peralkaline (Fig. 20), in contrast to the distinctly subalkaline biotite granite of the Drammen pluton. As a result, the characteristic primary dark minerals in this granite are arfvedsonite and ægirine / ægirine-augite. Biotite, if present, is formed by local, postmagmatic reaction between magnetite and alkali feldspar. Some varieties of "ekerite" contains rare, alkali-rich minerals. Astrophyllite ($(K,Na)_3(Fe,Mn)_7Ti_2Si_8(O,OH)_{31})$) is the most common of these (Neumann 1985), but it has so far not (?) been found on the locality to be visited.

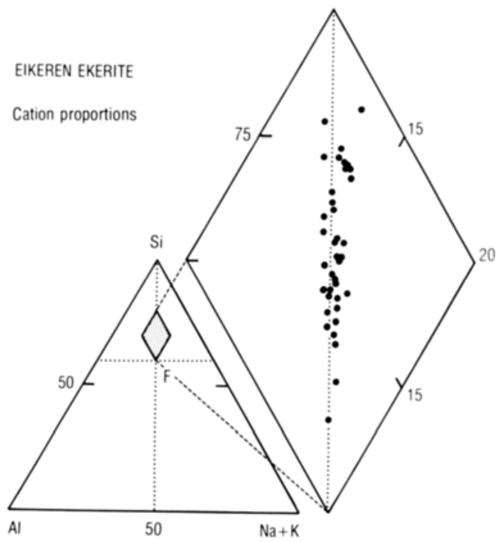


Figure 22
Whole-rock composition of alkali granite from the Eikeren pluton projected to the Si-Al-(Na+K) plane. The samples plot along the boundary line between alkaline and peralkaline compositions. From Neumann et al. (1990).

Overall, the Eikeren pluton is rather monotonous, with only local pegmatitic and aplitic domains. The rock has a distinct miarolitic texture with occational cavities outlined by well-formed quartz and alkali feldspar crystals. Fluid inclusions in quartz crystals from miarolitic cavities show an evolution from magmatic fluids with elevated alkali chloride and –sulphate contents (hydrosaline melts) to dilute alkali chloride fluids, caused by influx of meteoric water at the submagmatic stage. Some rare alkali sulphate minerals have been identified as daughter minerals in fluid inclusions (aphthitalite: $(K,Na)_3Na(SO_4)_2$, görgeyite: $K_2Ca_5(SO_4)_6$; Hansteen and Burke 1990).

Locality 2.7: Marginal intrusions of the Sande cauldron at Eidsfoss
Coordinates: 0555313 6612263

The cauldron structures of the Oslo Rift are collapsed central volcanoes formed during stage 4 of the rift evolution (Oftedahl 1978, Neumann et al. 2004). Most of the volcanic features of the Sande cauldron has been obliterated by later larvikite and nordmarkite intrusions (making up the hills north of Eidsfoss), but a group of volcanic feeder pipes has been preserved around Eidsfoss (Fig. 24), along the southern part of the ring fault (Andersen 1984).

The lavas outside of the ring fault belong to the lowermost part of the lava sequence (B1, RP1), the lavas of the downfaulted block has an uncertain stratigraphic status. Near the volcanic feeder pipes, lavas have been strongly brecciated, suggesting a quite explosive nature of the volcanic eruptions. Two distinct types of subvolcanic feeder pipes can be recognized: Those having only alkali feldspar phenycrysts (”trachyte”) and those also carrying (β) quartz phenycrysts, trachytic pipes are always older than the rhyolitic ones. Both rock types were originally glassy, and have steep flow banding.

South of the Sande cauldron, rhyolitic ignimbrites of unclear stratigraphic position crop out. Although these have traditionally been assigned to a separate, poorly defined cauldron structure (the Hillestad cauldron), but a connection to the subvolcanic feeders at Eidsfoss may perhaps be equally likely.

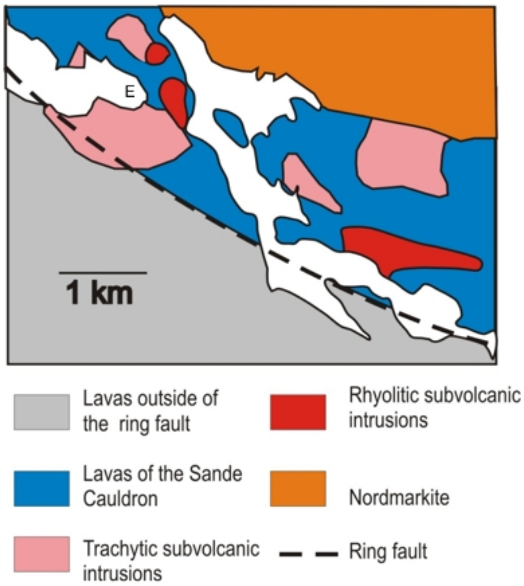


Fig. 24
Rocks from the caldera stage of the Sande central volcano exposed around Eidsfoss (E)

Day 3: Monday, August 4th, 2008

The Siljan-Mykle plutonic complex

The Siljan-Mykle intrusive complex makes up the western part of the Vestfold graben. It differs from other composite plutons in the Oslo Graben in the wide variety of rock types found – in fact, it spans the whole petrographic spectrum from gabbro and nepheline syenite to biotite granite and alkali granite (Fig. 25). Detailed field- and laboratory studies by staff and students from the Department of Geology at Copenhagen University, lead by Professor Henning Sørensen from 1987 and onwards has given a quite detailed insight into the structure and evolution of this intrusive complex (e.g. Pedersen and Sørensen 2003, Morogan and Sørensen 1994, Petersen 1992, Petersen and Sørensen 1997). Unfortunately, much of the area is rather inaccessible (forest, closed forestry roads). The fieldtrip will visit some key localities east and south of lake Mykle.

The following succession of magmatic events in the Mykle area has been established:

1. *Larvikite*, making up a large pluton which was most probably formed by several intrusive events.
2. Intrusion of small bodies of *gabbro/diorite* and *nepheline syenite*. The gabbro contains xenoliths of larvikite, and the larvikite is intersected by dikes of nepheline syenite, showing that the gabbros and nepheline syenites are younger than the larvikite. The gabbro and the nepheline syenite are themselves intruded by syenite and granite. The age relationship between gabbro and nepheline syenite is unknown.
3. Intrusion of small bodies of *porphyritic syenite* which contain xenoliths of larvikite and gabbro but are intersected by several generations of dikes of syenite and granite.
4. Bodies of *syenite* (nordmarkite) and *granite* which intersect the porphyritic syenite. They contain net-veined complexes in their contact zones with larvikite.
5. A large body of coarse-grained *alkali granite* of ekeritic type.

Larvikite and alkali granite units in the complex have given ID-TIMS U-Pb zircon ages of 280-281 Ma, without significant differences between the rock types (Pedersen et al. 1995).

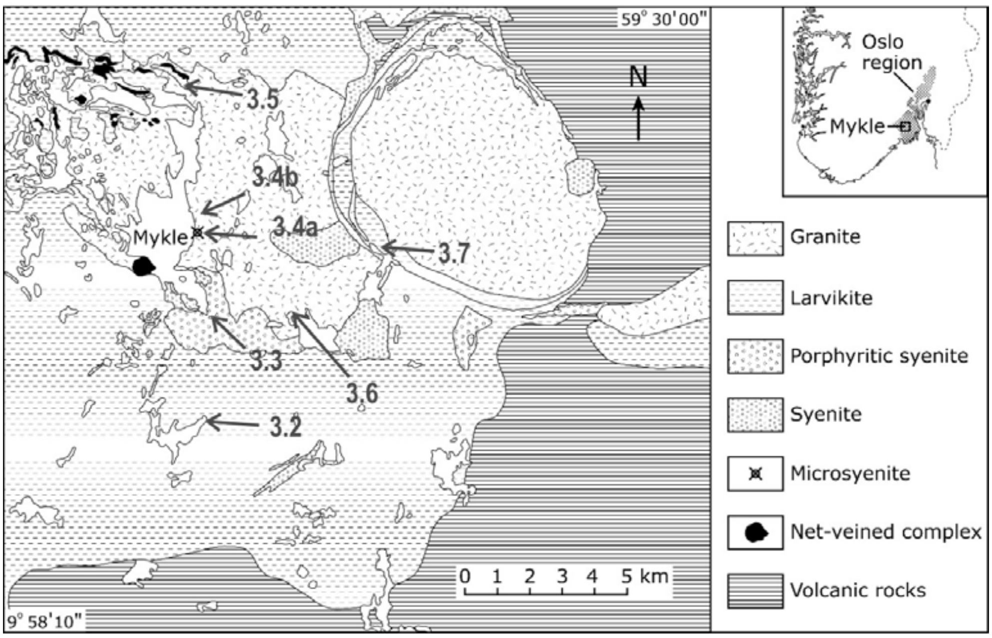


Fig. 25
Simplified geological map of the Siljan-Mykle intrusive complex (Andersen et al. 2004a)

Locality 3.1: *Nordmarkite in roadcut at Road 32*
Coordinates: 0545872 6573412

The nordmarkite exposed in roadcuts at the boundary between Vestfold and Telemark counties does not belong to the Siljan-Mykle complex itself, but to a separate ring-complex (Fig. 26) called the Siljan-Hvarnes complex by Pedersen et al. (1995). In addition to nordmarkite, it contains larvikite and a porphyritic syenite similar to the one at lake Mykle (locality 3.3).

The rock at this locality is a fairly typical example of nordmarkite: A pink alkali feldspar syenite with a very well developed miarolitic structure. Mafic minerals are an alkali amphibole and aegirine augite, always occurring interstitial to the feldspar. Small amounts of quartz are present, commonly as interstitial crystals with ideal terminations towards the interstitial cavities. Accessory minerals found at this locality include apatite, zircon and titanite, commonly as euhedral crystals in the miarolitic cavities.

A nordmarkite unit in the Siljan-Hvarnes complex similar to the one visited has been dated to 278.6±0.6 Ma by ID-TIMS U-Pb on zircon, which is identical within error to ages obtained from other syenitic and larvikitic units in this ring complex (Pedersen et al. 1995), which appears to be 1-2 Ma younger than the main Siljan-Mykle complex exposed further north.

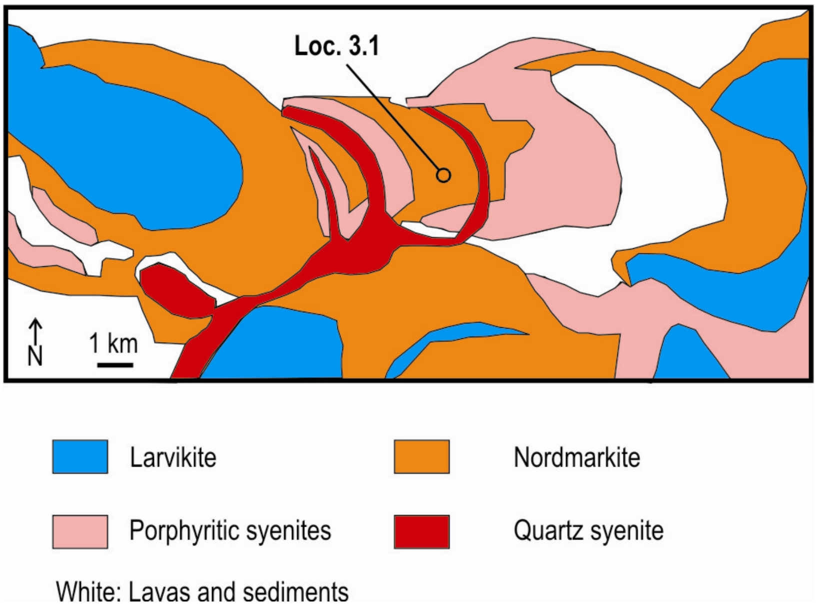


Fig. 26
Geological map of the Siljan-Hvarnes ring complex, simplified from Pedersen et al. (1995).

Locality 3.2: Larvikite, lake Sporevann

Coordinates: 0539529 6583023

Larvikite and associated rocks will be the main theme on Day 4. The present brief stop to look at shore exposures at lake Sporevann in the southern part of the Siljan-Mykle complex will show that larvikite is not always the beautiful ornamental stone well known from buildings and monuments. The rock at this locality is probably more representative of the large volumes of larvikite in the Oslo Graben.

The larvikite at lake Sporevann is a grey, medium- to coarse-grained rock with more or less exsolved ternary feldspar and interstitial dark minerals (sodic augite, amphibole, biotite, magnetite). The feldspar lacks the schiller effect that is characteristic for the varieties that are quarried.

In the Siljan-Mykle complex, larvikite makes up the earliest intrusive member. It is exposed in a roughly arc-shaped body along the southern and western margins of the complex. In the centre, around lake Mykle, it has been intruded by younger intrusive rocks (syenites, alkali granite) in such a way that the contact to larvikite is almost horizontal at a level some tens of metres above the level of the lake. The interference of the subhorizontal intrusive contact and the relatively rough topography causes the intricate outcrop pattern in the NW part of the geological map in Fig. 25.

Locality 3.3: The porphyritic syenite at lake Mykle
Coordinates: 0539700 6586540

At the south end of lake Mykle, an intrusive body of porphyritic syenite with grey, larvikite-like anorthoclase phenocrysts in a pink, alkali-feldspar dominated groundmass (Petersen and Sørensen 1997, Andersen et al. 2004a). This is one of the few rock types that were not recognized as special petrographic varieties by Brøgger and the other pioneers in the Oslo Rift – it has therefore never been given a petrographic name of its own.

Major and trace element data indicate a close genetic relationship with larvikite. The rocks shows limited variation in initial Sr and Nd isotope composition along a trend which can be attributed to contamination with Mesoproterozoic calcalkaline rocks at depth in the crust (Fig. 27, from Andersen et al 2004a).

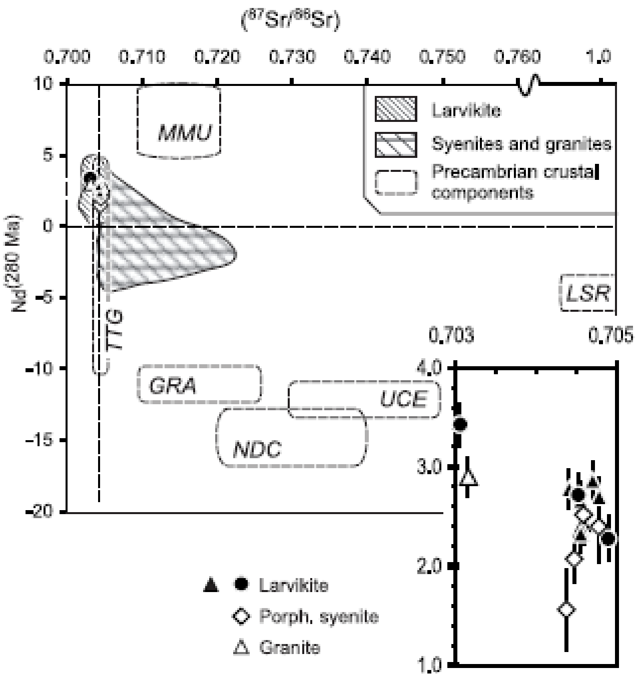


Fig. 27
Sr and Nd isotopic composition of porphyritic syenite and associated rocks from the Mykle area. Black triangles represent larvikites from NE of Lake Mykle. Ruled / cross-hatched areas represent ranges of regional variation of larvikite and syenite and granite in the Oslo Rift (data from Neumann et al. 1988). Ranges of Precambrian crustal components are taken from Andersen and Knudsen (2000): *MMU*: 1.15-1.50 Ga Mafic underplate, *GRA*: ca. 0.93 Ga grantites, *NDC*: "Normal deep crust", i.e. moderately LILE enriched rocks in the deep crust, *UCE*: Upper crustal rocks east of the rift, LSR: Upper crustal rocks of the Telemark area, showing elevated Rb/Sr ratios at normal Rb concentrations. *TTG:* Precambrian (1.6-1.2 Ga) calc-alkaline metaigneous rocks, including tonalite, trondhjemite, granodiorite and their extrusive equvialents (Knudsen and Andersen 1999, Andersen and Knudsen 2000 and references therein). The inset is an expansion of the rocks from the Mykle area, showing data points with 2σ error bars.

Locality 3.4a: *Microsyenite*
Coordinates: 0539352 6589009

A small body of microsyenite occurs at the east bank of lake Mykle, and can be observed in stream and roadcut exposures in a small area around the bridge across Smalvannelva river (Andersen and Sørensen 2003).

In terms of whole-rock composition, the rock is similar to extrusive trachytes interbedded in the rhomb-porphyry lava sequence of the Vestfold graben. The rock formed as a shallow (subvolcanic) intrusion into larvikite at stage 2 of the evolutionary history of the Siljan-Mykle complex. Today, it is preserved as a xenolith in the younger alkali granite to be seen at locality 3.4b.

The most interesting feature of this rock is its pyroxene mineralogy. Almost all pyroxene crystals are zoned, with a Na-augitic core and an aegirine-augite overgrowths (Fig. 28). The overgrowths are themselves zoned with increasing acmite towards the rims. The pyroxenes in this rock mimic the general compostional trends of pyroxene in larvikite (cores) and nordmarkite (rims).

Pyroxene and feldspar zonation patterns suggest that the trachytic magma developed through two distinct stages of evolution. The Mykle microsyenite is therefore a transitional rock type in the Oslo Rift, representing either a cogenetic 'missing link' between larvikitic and nordmarkitic trends of evolution, or a well-homogenized hybrid between the two.

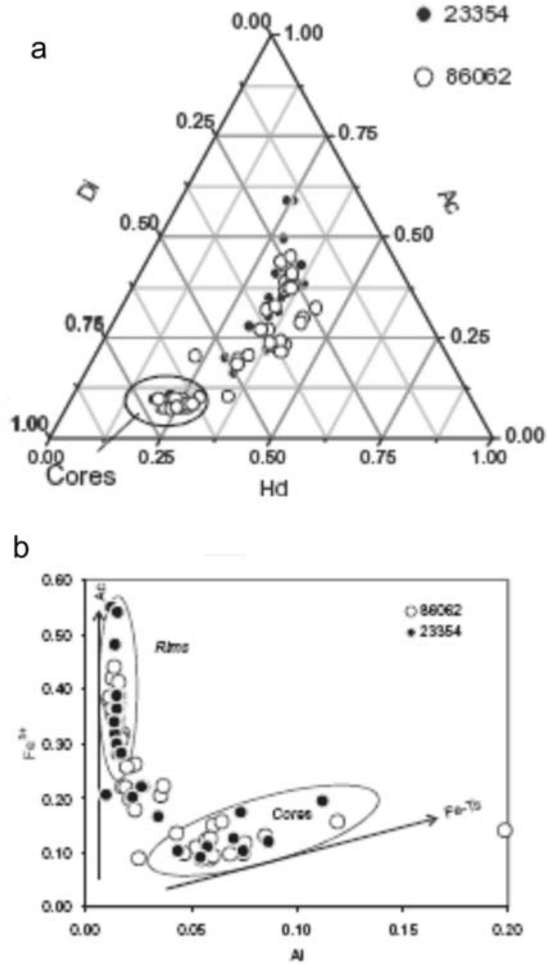


Fig. 27
a: Pyroxene compositions plotted in the Di-Hd-Ac plane
b: Plot of total calculated Fe^{3+} and Al in clinopyroxene, with arrows representing the acmite ($Mg_{M1}Ca_{M2}=Fe^{3+}_{M1}Na_{M2}$) and ferri-tschermak ($Mg_{M1}Si_{T}=Fe^{3+}_{M1}Al_{T}$) substitutions.
From Andersen and Sørensen (2003).

Locality 3.4b Miarolitic alkali granite
Coordinates: 0539312 6589308

The alkali granite at this locality is a more heterogeneous type than at Eikeren (locality 2.6). There are abundant miarolitic veins and cavities, rich in fluid inclusions. The alkali granite in the Mykle area occurs as distinct fine-grained and coarse-grained varieties, this is the finer-grained type. The coarse-grained granite is in general more strongly peralkaline (Fig. 29). The following summary from Bonin and Sørensen (2003) gives their main findings on these granites:

The granites exposed around lake Mykle constitute a western and an eastern massif. Only the western massif is treated by Bonin and Sørensen (2003). It forms an intrusive complex with the following characteristics:

* Country rocks are larvikite occurring in the topographic highs and as stoped blocks within the granites.

* Two types of granite were identified: an early, marginal, fine- to medium-grained, reddish granite; and a younger, central, coarse-grained, white to grey ekerite.

* The fine- to medium-grained reddish granite displays chilled margins at the contacts with larvikite and locally contains mafic rocks as net-veined complexes.The granite, akin to type BG 2 of the biotite granite classification of Gaut (1981), is metaluminous to weakly peraluminous and yields the highest contents of incompatible elements.

* Though later than syenite and the fine- to mediumgrained granite, the ekerite displays sharp contacts only, with no chilled margins, indicating that no significant temperature gradients were created during its emplacement.

* Miarolitic cavities, abundant in all rock types, are evidence of fluid exsolution from volatile-rich magmas and continuing transfer of fluids at subsolidus temperatures.

* The present surface level corresponds to the poorly exposed roof of a larger intrusion, emplaced within larvikite and rhomb porphyry lavas by magmatic stoping and perhaps by cauldron subsidence.

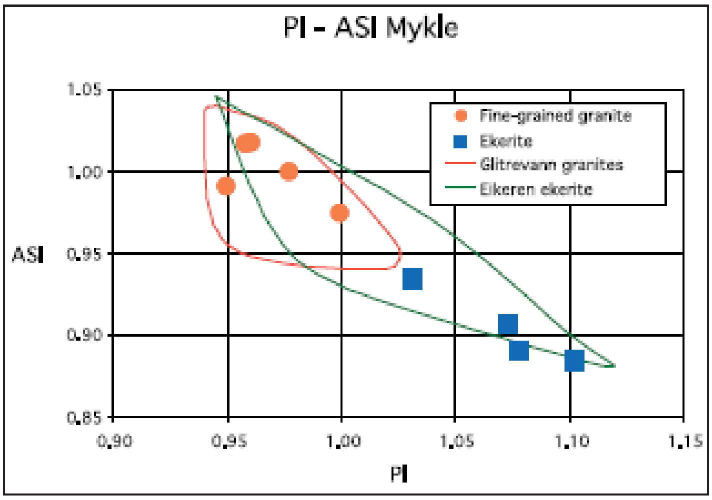


Fig. 29
PI-ASI diagram for granitic rocks in teh Siljan-Mykle complex, from Bonin and Sørensen (2003). The Alumina Saturation Index is defined as the $Al_2O_3/(CaO + Na_2O + K_2O)$ molar ratio. The Peralkalinity Index PI is defined as the $(Na_2O + K_2O)/ Al_2O_3$ molar ratio. The polygonal areas are the composition fields of the Glitrevann cauldron (adapted from Jensen 1985) and the Eikeren ekerite (adapted from Neumann et al. 1990).

Locality 3.5: *Mafic-felsic mingling complexes in alkali granite.*
Coordinates: 0538426 6594136

Net-veined complexes composed of globular masses of fine-grained basic igneous rocks and veins of coarser-grained syenitic and granitic rocks occur in the complicated contact zone of a body of granite which intrudes into plutonic masses of larvikite around lake Mykle. The best outcrops are at the western shore of the lake, which for logistical reasons cannot be visited by the excursion. Smaller examples are found along the forestry road NW of the lake.

The results of Morogan and Sørensen (1994) indicate that magma of basaltic trachyandesite were emplaced into a granitic or syenitic magma chamber and rose along the walls of the chamber in a zone of weakness between a marginal shell of already consolidated granite and the main mass of still at least partially fluid granitic magma. The trachyandesite formed sheets along the walls which were invaded by several generations of veins of syenite.

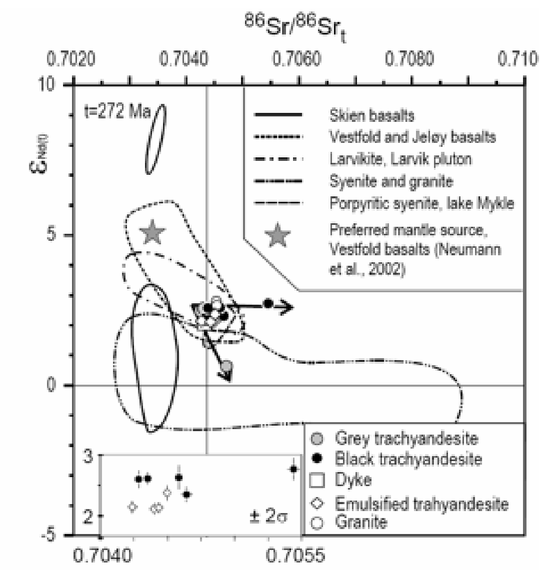


Fig. 30
Sr and Nd isotopic compositions at 272 Ma. The expanded detail
in the lower left part of the diagram shows the compositions of black and emulsified trachyandesites at 272 Ma, with ±2σ error bars, where
these exceed the symbol size (symbols as in the main part of the figure).
Black arrows:Mixing trends illustrating hydrothermal (horizontal arrow)
and bulk (sloping arrow) contamination trends of mantle-derived
magma with old, crustal material. Sources of reference data: Skien
basalts: Dunworth et al. (2001), Vestfold and Jeløy basalts: Neumann et
al. (2002), Larvikite, syenite and granite: Neumann et al. 1988, Trønnes and
Brandon (1992), Porphyritic syenite: Andersen et al. (2004a). The dike is a disrupted basic dyke described by Morogan and Sørensen (1994).
The figure has been taken from Andersen et al. (2004c).

Morogan and Sørensen (1994) distinguished three types of basaltic trachyandesite: *grey, black* and *hybrid*. The grey type is slightly more coarse-grained than the black type. Three stages of crystallization were observed in the black type: 1. Macrocrysts of plagioclase and clinopyroxene; 2. Granular amphibole, biotite, clinopyroxene, feldspar, iron-titanium oxides, apatite and titanite; some quartz was also formed in the grey rock at this stage. 3. A dense matrix of feldspar, clinopyroxene, amphibole, biotite, titanite and a multitude of apatite needles and skeletal crystals of iron-titanium oxides. Only stages 1 and 2 are present in the grey type. Xenocrysts of clinopyroxene and plagioclase indicate that the basaltic trachyandesitic magmas were formed by mixing of basaltic and trachytic magmas.Trachyandesites containing grains of quartz and potassium feldspar represent the hybrid type.

Strontium and neodymium isotope data (Andersen et al. 2004c) indicate that the trachyandesitic component in the net-veined complexes is either genetically related to larvikite or basaltic lavas of the Vestfold-Jeløya type, or derived from a similar mantle source (Fig. 30). Variations in initial Sr isotope compositions in the trachyandesite, which are uncorrelated with Nd isotopes, are due to selective introduction of more radiogenic Sr by a fluid phase before or during emplacement of the trachyandesitic melt.

Locality 3.6: The Raubern nepheline syenite and its contact relationships
Coordinates: 0542373 6586276

The Raubern nepheline syenite is a rare example of silica-undersaturated rocks occurring outside of the Larvik complex. The excursion will visit a roadcut outcrop showing a complete section through the best studied among several minor bodies of nepheline syenite totally enclosed in alkali granite (Fig. 31).

The first impression of this rock is a paradox: Although it is clearly a nepheline syenite, some thin sections contain quartz as well as fresh nepheline (!). The explanation of this anomaly is the post-intrusive history of the rock. The Raubern nepheline syenite belongs to stage 2 of the evolutionary history of the complex, and has later been all but engulfed by later intrusions (granite and syenite). Along the contacts to alkali granite, the nepheline syenite has reacted, leaving behind a mass of general syenitic composition. This can be observed on both outcrop and thin-section scale, so that domains of fresh nepheline syenite, alkali granite veins and the altered zone in-between can be present in a single thin section.

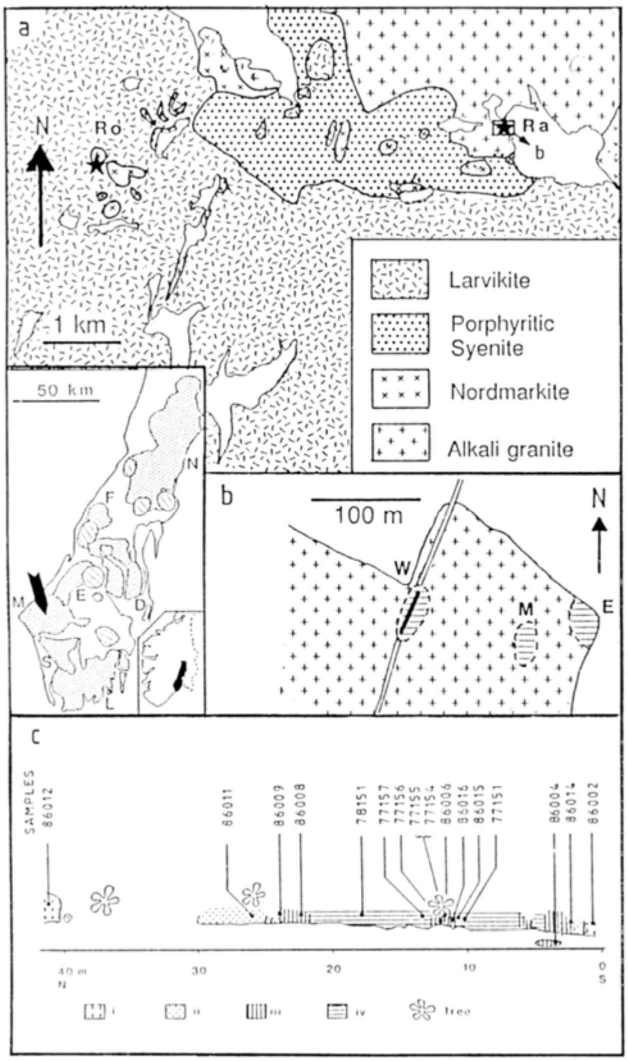


Fig. 31
Geological map and profile through the Raubern nepheline syenite.
a: Map of part of the Siljan-Mykle complex showing occurrences of nepheline syenite enclaves in granite at Raubern (Ra) and Romsdal (Ro).
b: The three main nepheline syenite enclaves at lake Raubern (ruled). The heavy line through the westernmost enclave is the roadcut profile sketched in c.
c: Map of the roadcut section (use the marked trees for exact orientation), with samples analysed by Andersen and Sørensen (1993).

The rock is somewhat more aluminous than other nepheline syenites in the Oslo Rift, resulting in a slightly exotic mineralogy, with more aluminous clinopyroxene (high ferri-aluminium Tschermak's component) and amphibole than seen in other rock types, as well as late magmatic hydroandradite garnet, analcime and zeolites (Table 3).

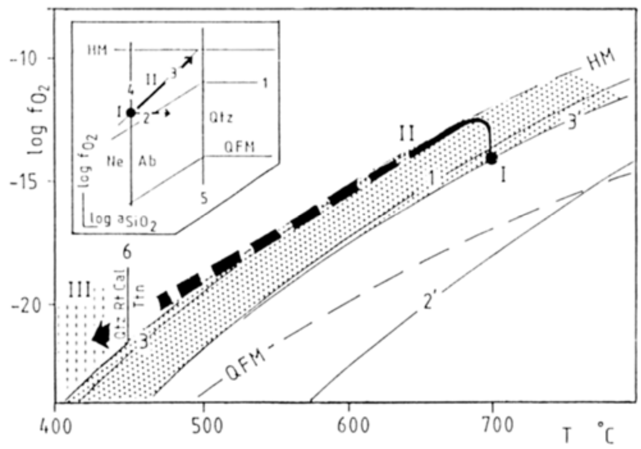
The peculiar mineralogy of the rock can be explained by a post-magmatic cooling history at increasing oxygen fugacity and silica activity (see T-*log* f_{O2} section, Fig. 32).

Table 3. Mineralogy of nepheline syenite enclaves at lake Raubern (Andersen and Sørensen 1993).

Indicator minerals	Paragenetic setting		
	I + Ne + Ttn	II − Ne + Ttn	III − Ne − Ttn
Early magmatic minerals			
Nepheline	+	−	−
Feldspar (unexsolved)	+/−	−	−
Clinopyroxene (cpxI)	+	+/−	−
Apatite	+	+	+
Magnetite	+	+	+/−
Titanite	+	+	−
Late magmatic minerals			
Perthite	+	+	+
Nepheline pseudomorphs	−	+	+
Analcime	+	+	?
Sodalite	+	?	?
Amphibole	+/−	+/−	−
Ti-Garnet	+/−	−	−
Late magmatic or metasomatic minerals			
Clinopyroxene (cpxII)	+	+/−	−
Hydroandradite	+	+	+/−
Biotite	−	+	+/−
Gonnardite	−	+	?
Thomsonite	−	+	?
Fluorite	?	+	+
'Ilmenite' (lamellae)	?	+	+
Epidote	−	+/−	?
Metasomatic minerals			
Rutile	−	−	+
Calcite	−	+	+
Hematite	−	−	+
'Allophane'	+	+	−
White mica ('sericite')	−	+	?
Quartz in pseudomorphs	−	−/?	+/−
Quartz (miarolitic)	−	+/−	?
Cheralite (?)	−	(+)	−

Paragenetic settings: Column I (+Ne+Ttn): The minerals indicated by a + sign occur in textural equilibrium with unaltered nepheline and titanite. Column II: The minerals indicated with + occur together with titanite and altered nepheline. The minerals which have + in column III are found in settings with altered nepheline and altered titanite. Some minerals are found in two or three of the paragenetic settings, others show different behaviour at different samples. The latter are indicated by the symbol +/−. Question marks indicate that the relationships are unclear, or the data insufficient.

Fig. 32
T-f_{O2}-log a_{SiO2} relationships during crystallization of the Raubern nepheline syenite, showing conditions during the three distinct stages of evolution that can be inferred for the nepheline syenite enclaves: (1): Primary magmatic crystallization, (2): Post-magmatic oxidation and cooling, (3): Alteration in the granitic magma.



Locality 3.7 (optional stop): The Prestseter larvikite
Coordinates: 0545017 6588527

The Prestseter larvikite is a separate intrusion that appears to penetrate the syenitic rocks of the Siljan-Mykle complex. It must therefore belong to a considerably younger stage of the intrusive history than the main larvikite body in the complex, which was seen at Sporevann. The larvikite at this locality is dark and relatively coarse-grained, again without iridiscent feldspar.

Locality 3.8: *Nepheline syenite and lardalite at Gjone*
Coordinates: 0556298 6560283

On this locality we can observe one of the youngest and most evolved intrusive rocks in the Larvik pluton (Fig. 33), a nepheline syenite, with poorly exposed intrusive contact to lardalite (the *hedrumite* of Brøgger 1906). The genetical relationship of this nepheline syenite to the other rock types in the pluton is far from clear. The rock is almost white in colour, and characterized by a well-developed trachytoid texture. It weathers badly.

The rock consists of platy, white alkali feldspar with interstitial nepheline, sodalite, biotite, aegirine and Fe-Ti oxides.

Near the main road there are low and badly weathered roadcuts with a medium-grained variety of lardalite, which is intruded by the nepheline syenite.

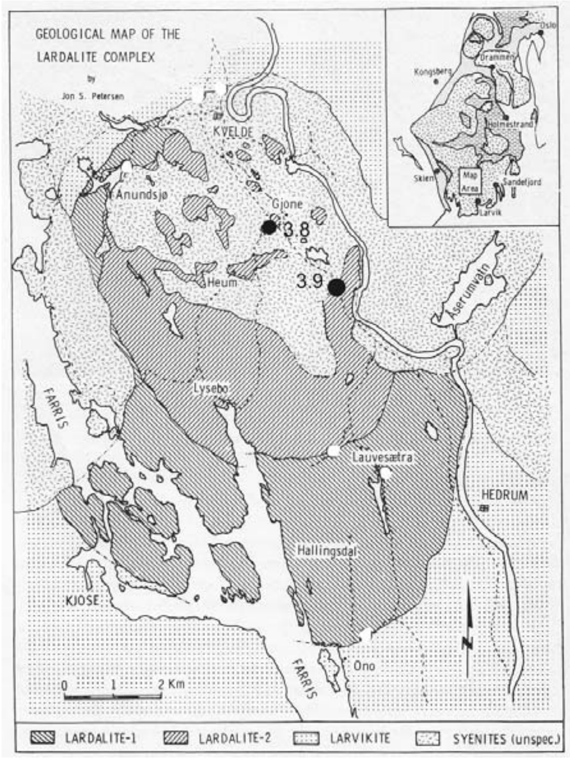


Figure 33
Geological map of the lardalite intrusions in the Larvik plutonic complex and crosscutting syenitic rocks. From Oftedahl and Petersen (1978)

Locality 3.9: Coarse-grained lardalite, roadcut south of Gjone
Coordinates: 0557692 6558794

Roadcut stop at a busy road BE CAREFUL !

The two youngest ring-segments in the Larvik pluton are made up by lardalite – a series of plagiofoyaite – nepheline monzonite rock types (Fig. 33). Although genetically related to larvikite and the other intermediate rocks of the Oslo Rift, they are not simple comagmatic differentiates of slightly older larvikite magmas, but must represent a separate trend of evolution. Lardalite varies somewhat in mineralogy and grain-size. At the roadside exposure visited by the excursion, we can find a coarse-grained rock whose feldspar is strongly resemblent of that of larvikte. Mafic minerals are pyroxene and, possibly, olivine.

Day 4: Tuesday, August 5th, 2008

The program on the final day is related to the rocks of the Larvik pluton. This composite intrusion formed during stage 3 of rift evolution (Table 1). Mapping by Petersen (1978) showed that the pluton is formed as a series of nested ring-shaped intrusion (Fig. 3).

Locality 4.1: Sagåsen - Larvikite quarry and nepheline syenite pegmatite

Coordinates: 054707 6545456

The Sagåsen quarry produces larvikite of the ”Blue Pearl” or Tvedal type (Fig. 5). The first stage of quarrying at this site started in 1970 and lasted until 1994. During development of the quarry, a large nepheline syenite pegmatite rich in rare minerals was uncovered and removed as part of the operation. The present quarry (Fig. 6) is at a deeper level in the hill. Again, a large nepheline syenite pegmatite has been uncovered, and can be studied in-situ in wire-cut horizontal and vertical faces which giving an almost complete cross section of the dike (Fig. 34). The pegmatite has an agapitic mineralogy with microcline, nepheline, sodalite, eudialyte-group species (ferrokentbrooksite), wöhlerite and leucophane as prominent minerals (Fig. 35). A full list of minerals reported from the locality is given in Table 4.

The pegmatitte has no value as ornamental or dimension stone, and is treated as waste in the quarry. Both the characteristic major mineral assemblage of the pegmatite and rare minerals can be found in blocks in the waste dumps in the quarry.

Fig. 34
Vertical cross-section through the Sagåsen nepheline syenite pegmatite. Note the directional growth of large crystals of microcline perpendicular to the upper contact, and the foliated nature of the wall rock immediately above.

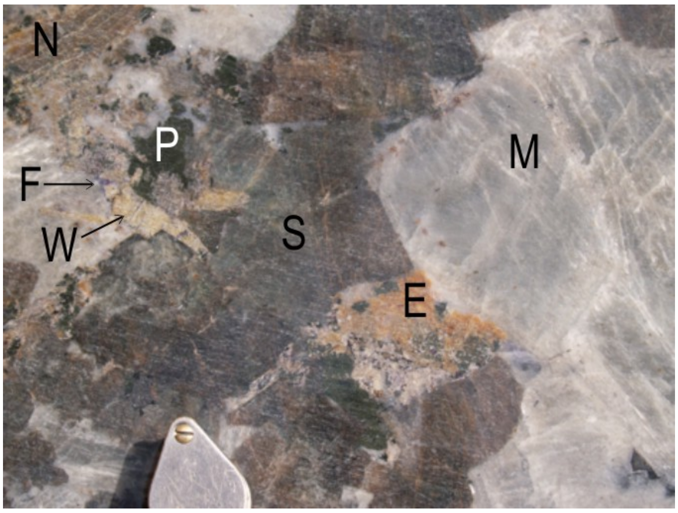


Fig.35
Minerals of the Sagåsen nepheline syenite pegmatite, seen in a wire-sawed section at the quarry floor.
M: Microcline, S: Sodalite, N: Altered nepheline, E: Eudialyte (Ferrokentbrooksite), W: Wöhlerite, F: Fluorite, P: Pyroxene (aegirine or aegirine-augite). The hand lens for scale is ca. 20 mm across.

Table 4: Minerals reported from the Sagåsen quarry (source of data: www.mindat.org).

Aegirine	Ferrokentbrooksite	Nepheline
Albite	Fluorite	Nordstrandite
Analcime	Galena	Parisite-(Ce)
Ancylite-(Ce)	Gibbsite	Pectolite
Annite ?	Goethite	Polylithionite
Apatite-(CaF)	Gonnardite	Powellite
var: Carbonate-rich Apatite-(CaF)	Gonyerite	Pyrite
Apophyllite-(KF)	Hambergite	Pyrochlore
Arsenopyrite	Helvite	Pyrophanite
Astrophyllite	Hematite	Pyrrhotite
Bastnäsite-(Ce)	Heulandite-Ca	Rhodochrosite
Behoite	Hydrocerussite	Rosenbuschite
Berborite	Ilmenite	Sodalite
Biotite	Kentbrooksite	Sphalerite
Böhmite	Låvenite	Tadzhikite-(Ce)
Britholite-(Ce)	Leucophanite	Thomsonite-Ca
Calcite	Löllingite	Thorite
Cancrinite	Microcline	Tritomite-(Ce)
Catapleiite	Molybdenite	Tvedalite
Cerite-(Ce)	Monazite-(Ce)	Wöhlerite
Chiavennite	Montmorillonite	Wulfenite
'Chlorite Group'	Mosandrite	Zircon
Epididymite	Natrolite	Zirsilite-(Ce)
Eudidymite	Neotocite	

Locality 4.2. Layered larvikite and moonstone-pegmatites, Ula
Coordinates: 0567970 6543436

Layered larvikite will be examined in shore cliffs at Ula (Fig. 36). The larvikite at Ula is a grey, nepehline-bearing variety (”Kjerringvik type” in Fig. 5) which belongs to unit IV in Petersen’s (1978) intrusive chronology (Fig. 3)

In the southernmost part of the Larvik pluton, the larvikite has locally developed an orientational fabric defined by parallel orientation of lath-shaped feldspars. This can, for example, be seen in some of the commercial varieties of pale larvikite (”Blue Pearl”). Rhytmic and graded igenous layering is also found locally. The layering is commonly steep and inwards-dipping, and is defined by a basal concentration of Fe-Ti oxides and mafic silicates, grading upwards into feldspar- richer compositions. Individual rhytmic units can be 10-20 cm thick, and layered zones commonly up to 5 m, grading into unlayered larvikite with an orientational fabric (Petersen 1978).

The larvikite is cut by syenitic pegmatites of the eastern or ”Stavern” type, with anorthoclase crystals showing an uncommonly well-developed schiller effect. *The pegmatites are protected by law – absolutely no sampling or hammering is allowed !!*

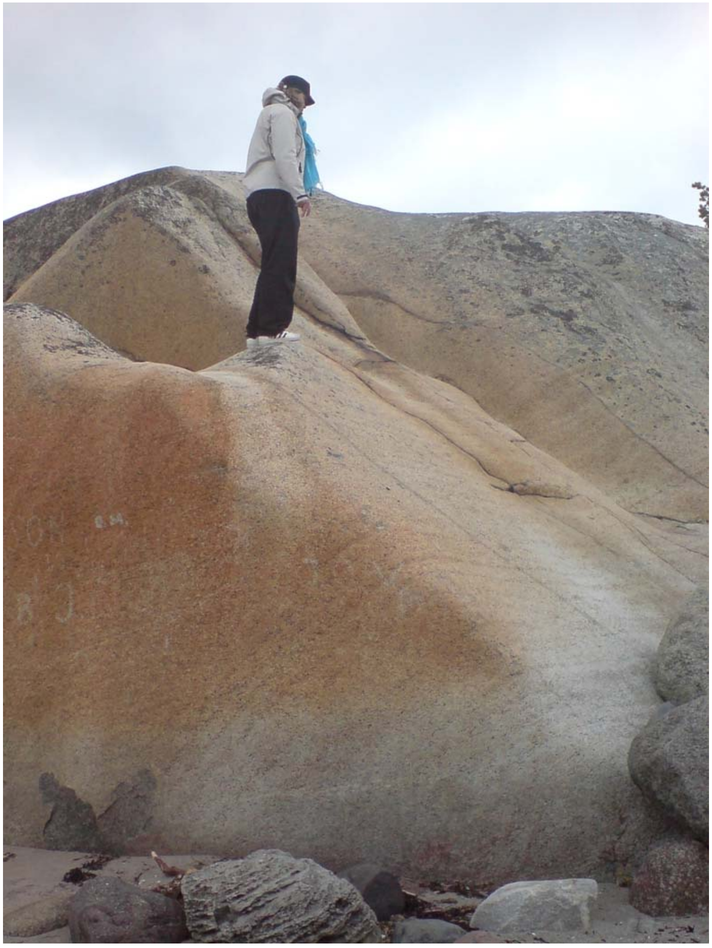


Fig. 36
Shore cliffs at Ula showing larvikite with well-developed, steeply dipping rhytmic layering.

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