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Structure of the Larvikite-Lardalite Complex, Oslo-Region, Norway, and its Evolution

By Jon Steen PETERSEN, Oslo *)

With 5 figures

Zusammenfassung

Die Arbeit behandelt bisher nicht beschriebene Strukturen im südlichen Teil des permischen Bruchsenkungsgebietes im Oslogebiet in Norwegen. Sie zeigen, daß das Larvikit-Massiv einen ringförmigen Komplex bildet aus zahlreichen, ungefähr zirkulären und untereinander diskordanten Teilbereichen. Die Lage der Diskordanzen erlaubt die Annahme, einer westlich gerichteten sukzessiven Verlagerung der Zentren magmatischer Aktivität. Mit abnehmendem Alter dieser Teilbereiche verändert sich deren Mineralbestand von quartzführend über intermediär hin zur larvikitischen und lardalitischen Zusammensetzung mit Nephelinüberschuß.

Da dieser Komplex fast den gesamten Bereich des Osloer Bruchsenkungsgebietes deckt, stellt er ein wichtiges Profil durch die Grabenstruktur dar. Dieses läßt plausibel erscheinen, daß die Zentren der magmatischen Vorgänge der Gegend einem einheitlich westgerichteten Trend gefolgt sind gleichviel, ob man in ihnen großräumige Vorgänge ringförmiger Magmen-intrusion sieht oder zylindrische Kesselbrüche („Cauldrons"). Die in der Arbeit

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dargelegten Ergebnisse sind somit geeignet, die Frage des Ursprungs und der Entwicklung des Osloer Bruchsenkungsgebietes weiter zu erhellen.

Abstract

Structures not previously described from the southern part of the Permian rift-system in the Oslo-district, Norway, are presented. These indicate that the larvikite massif is a ring complex consisting of numerous individual sections which are roughly circular and repeatedly cut each other in a manner that suggests sequential shifting of centres of igneous activity towards the west. The compositions of these sections vary from quartz-bearing varieties in the earliest parts through intermediate types to larvikite and lardalite with excess nepheline in the youngest parts.

As this complex covers almost the total width of the Oslo rift-system, it forms an important profile across the graben structure. It suggests unilateral westward migration of centres of igneous activity in this region, viewed either as magma injection or cauldron subsidence and therefore provides additional information regarding the origin and evolution of the Oslo paleo-rift system.

Résumé

Une nouvelle analyse structurale de massif de larvikite au sud du rift permien d'Oslo, Norvège, montre que ce massif forme un complexe annulaire comprenant de nombreuses composantes à peu pres circulaires et discordantes entre elles. Les segments se recoupent successivement indiquant un déplacement des centres d'activité magmatique vers l'ouest. Les larvikites passent de types à composition acide avec quartz dans les premiers segments, à des types intermédiaires puis a des compositions sousatourée avec néphéline en excess dans les segments les plus jeunes.

Comme le massif occupe presque toute la largeur du rift d'Oslo il constitue une coupe importante de cette fosse paléozoique. Sa structure suggère une migration continue vers l'ouest des centres d'activité volcanique pour autant qu'on y voie des intrusions annulaires de magma, ou des effondrements successifs de la caldeira. Ce résultat apporte une information nouvelle sur l'origine et l'évolution du rift permien d'Oslo au sud de la Norvège.

Краткое содержание

Рассмотрены до сих пор не исследованные структуры на южной части зоны разломов пермского возраста в районе Осло, Норвегия. Доказано, что массив Ларвикит образует кольцевоподобный комплекс из многочисленных, располагающихся примерно концентрически, а по отношению друг ко другу — несогласно, секторов. Положение несогласий разрешает предполагать, что центры магматической актовности перемещались постепенно на запад. С уменьшением возраста этих зон изменяется и минералогический состав их от кварцевого через средний у ларвикитовому и лардалитическому составу с избытком нефелина.

Т. к. этот комплекс охватывает всю территорию разломов в районе Осло, то он оказывается важным профилем для изучения структуры грабена. Кажется логичным, что центры магматических процессов района при их смещении следовали единой тенденции на запад не зависимо от того, рассматривают-ли их, как обширные явления кольцевых интрузий магмы, или же цилиндрические разломы «котла» — «Cauldrons». Эта работа дает возможность решать вопрос, как о происхождении, так и о развитии зон разломов в районе Осло.

Structure of the larvikite-lardalite complex, Oslo-region, Norway and its evolution

The southernmost part of the Permian rift-system in the Oslo-district is made up essentially of larvikite (= monzonite) which here occupies more than 1000 km^2 (Fig. 1).

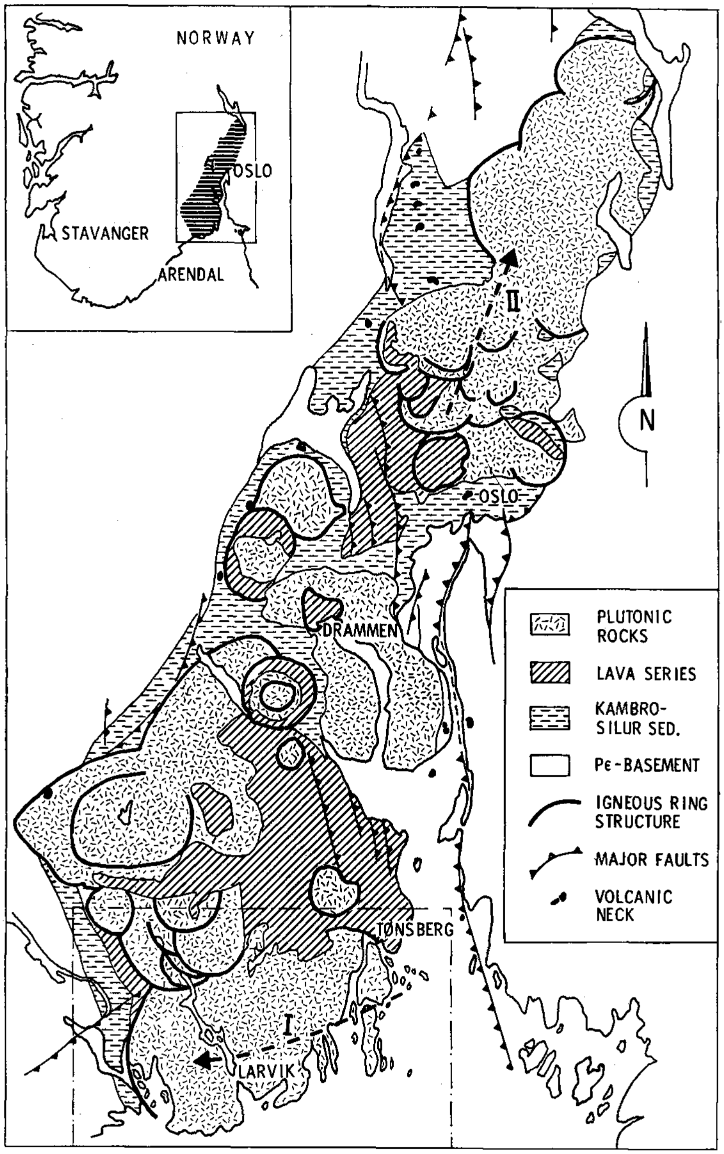

Fig. 1. Geological sketch map of the Oslo region, based on geological maps by BRØGGER & SCHETELIG (1923) and OFTEDAHL (1960 a) with minor changes and additions.

It is bordered to the NW by a nordmarkite-ekerite series; to the NE by extensive lava flows, essentially rhomb porphyries (latites) (OFTEDAHL, 1967); and towards the W, the complex cuts a series of Cambro-Silurian sediments and Permian lavas deposited on Precambrian gneisses outside the rift-valley (BRØGGER, 1883; OFTEDAHL, 1960).

The complex has been thoroughly studied by BRØGGER (1890, 1898), and a geological map published by BRØGGER & SCHETELIG (1923). Geochemistry of some of these rocks was compiled by BRØGGER (1933) and petrographic characters reviewed by BARTH (1944).

Recent field work in the area has indicated that the larvikite complex displays a large number of circular structures, which are arranged in a manner that suggest a general shift of focus towards the west. The purpose of the present work is therefore to present evidence of previously undescribed structures found in the southernmost larvikite-complex; to draw attention to a pattern which relates different larvikitic variants in a manner that points to a unilateral development of the complex; and to suggest some petrogenetically significant indications of this interpretation.

EVIDENCE FROM:

I Topographic effects

A number of striking lineaments appear on topographic maps and aerial photographs of the larvikite area. Some of these are rectlinear trending roughly NNW—SSE such as the Farris-Larviksfjord or the Lågen valley. This is parallel to major fracture directions in the southern part of the Oslo-province which are most likely the result of regional faulting related to the rift formation (OFTEDAHL, 1952). Numerous small camptonite dikes in the larvikite area generally follow this direction.

A great number of topographic lineaments however, are curvelinear and appear as topographic steps, narrow depressions, small streams and lakes as well as elongate hills, often situated in rows. Fig. (2) indicates that some of these lineaments, as interpreted from topographic maps and areal photographs, may suggest a concentric pattern apparently with centers progressively displaced westwards.

Where these lineaments are absent the topography is generally low, and these areas often consist of younger syenites which possess a conspicuous subhorizontal jointing, in contrast to many of the larvikite-lardalite rocks, and thereby have different geomorphological properties. These syenites correspond to rocks previously described as belonging to a foyaite-hedrumite-pulaskite series. Remapping has revealed that these rocks clearly postdate the larvikite-lardalite complex, and are therefore not included in this structural analysis.

Furthermore it should be noted that east of a line through Tønsberg-Sandefjord-Larvik (defined by the main road E-18) and further from Larvik towards Helgeroa (A-road 302), there is a marked contrast in topography. This is approximately the position of the huge Quarternary terminal Ra-moraine, which can be traced for several hundreds of kilometres across southernmost Norway. The direction of this line is NNE—SSW, roughly parallel to another principal direction in the Oslo-rift province, as well as forming the extension of the coast line of SE-Norway (Fig. 1), and may therefore possibly be related to regional faulting. In the lowlands to the south-east of this line some curvelinear topographic features occur, mostly as elongate hills and islands, and therefore topographic analysis is also possible in this area.

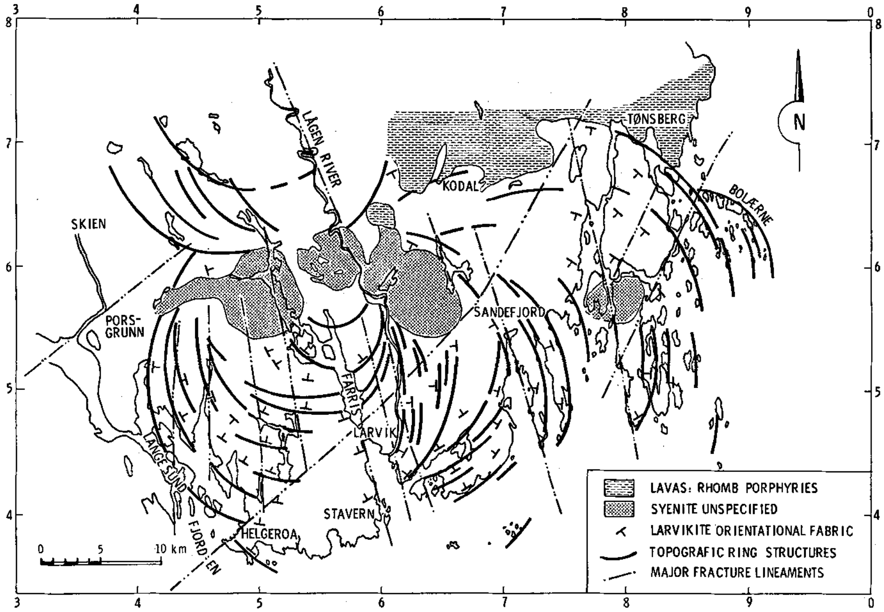

Fig. 2. Major structural lineaments in the larvikite district of the southern Oslo region. The curved lineaments suggest a general shift in centers of activity towards West, across the graben structure.

The presence of circular topographic structure-patterns in the Oslo province has been shown to be most clearly demonstrated by the numerous cauldron structures (Oftedahl, 1953; Sæther, 1962; Naterstad, 1971) but have also been recognized in many of the plutonic rocks series, both in areas north and south of Oslo (Sæther, 1962; Segalstad, 1975).

It has been suggested that these ring structures represent cauldron roots in the plutonic series and that the topographic effects reflect internal structures of the plutonic rocks in question (Segalstad, 1975). From the present study this seems also to be the case in the larvikite complex, when compared with the orientational fabric found in the area. However, the repeately off-centered character of the structures makes their origin as possible cauldron roots complicated and could be alternatively explained by originating as multiply intruded masses, possibly related to successive extrusive episodes in the region.

II Orientational Fabric

The common view of larvikite has been of a fairly homogeneous plutonic rock without any or only possessing a faint s-surface. However, in the southernmost complex the larvikite in large parts displays an orientational fabric, generally caused by the parallel arrangement of elongated rhomb-shaped feldspars. The mafic minerals often possess obvious interstitial, irregular and angular shapes.

Although hardly mentioned in previous descriptions of larvikite, rhythmic and graded igneous lamination is locally present. This is often developed as a concentration of oxides and mafic phases at the base of a layer, which gradually diminish in amount inwards and upwards, essentially at the expense of feldspars (Fig. 3). Occasionally, these basal layers develop as minor oxide ore-bodies, several dm thick. When found as massive bodies, they often appear to fill depressions in the layering and therefore wedge out along the strike of normal layering.

It is interesting to note that the presence of a large so-called jacupirangite-dike near Kodal (BERGSTØL, 1972) apparently seems to occupy such a position and displays similar geological characters such as conformity with larvikite orientational fabric, appropriate mineralogical composition, and lensoid shape. Furthermore a strongly asymmetrical contact zone (P. A. LINDBERG, pers. comm.) suggests a structural relationship to the layering in the surrounding larvikite. A cumulative origin for such apatite-rich oxide ores is implied for the region.

The rhythmic layering is often found in bands ranging from about 5 m to more than 50 m in width and surrounded by more homogeneous parts which, however, often possess an orientational fabric. The individual layers are in the order one to two dm thick (Fig. 3).

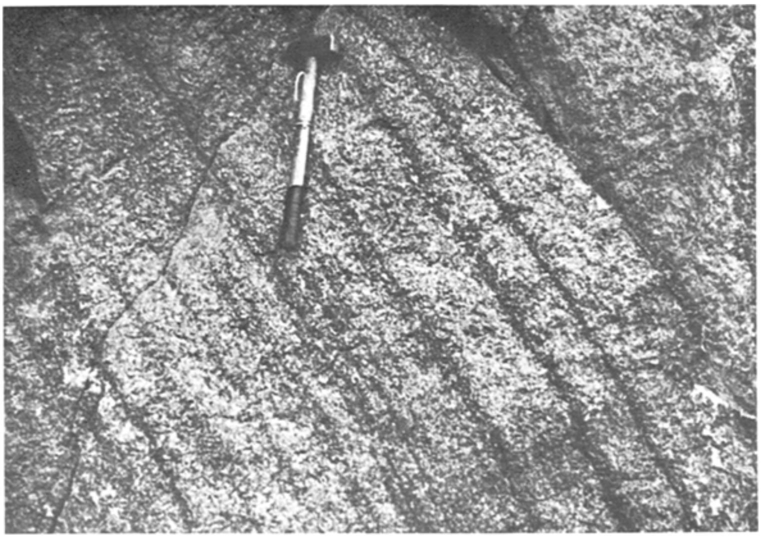

Fig. 3. Igneous lamination in larvikite is often developed as rhytmic layered zones within more homogeneous parts. From Vassvik near Farrisvann, NW of Larvik. The slightly curved appearance of the layering on the photo is caused by a convex nature of the exposure.

Generally the orientation of the layering fabric dips between 50° and 70° inwards towards the center of a ring structure and dips below 30° have only rarely been encountered. When two ring structures are in contact there may be a marked tendency towards a steeper orientation in the outer parts and a gentle decrease in dip towards the center. These relations are not always clear, possibly due in some cases to unidentified sections or subsections which may cut the structure concentrically and are therefore not easily recognized.

The orientations of layered structures, as well as the planar orientation of elongate feldspars, apparently closely follow the topographic features previously described. This suggests that they represent important primary structural elements in the larvikite massif, and are therefore significant features in the interpretation of the complex.

III Contact features

Within the larvikite massif are occasionally found zones between 4 and 50 m wide with fine grained variants following the curvilenear structure elements. Locally a gradation between aphyric, fine grained varieties through porphyritic types to normal coarse grained larvikite is found. Crystal morphologies of essentially alkali feldspar in these fine grained varieties reveal slightly curved crystals arranged in plumose branching patterns on a scale of 0.5—1 cm. Readily accessible examples of such zones are exposed along road cuts near Saga (U. T. M. grid ref. 465—480, Porsgrunn map sheet) from Årøa in the Langesundsfjord and near Nevlungshavn in the southernmost part of the region. The latter two represent border zones of the larvikite massif, whereas the former constitutes an internal boundary between two larvikite sections. Larvikite variants showing transitions to rhomp porphyry are other contact types which are essentially found along the northern boundary of the complex, west of Tønsberg, but occasionally also in other parts of the region.

The discovery of some conspicious textures along an internal boundary between two lardalite variants led the present author to regard the Lardalite complex of Brøgger (1898) as consisting of two individual and roughly circular sections, slightly displaced relative to each other and trangressed by a younger foyaite-syenite-series. A similar contact zone was also found along the southwestern larvikite-lardalite boundary, providing evidence for a multiple origin of this complex.

The most pronounced feature of these contact zones is a mesoscopical development of curved branching crystal morphologies for feldspar, pyroxene and nepheline in successive zones within a porphyritic, rather fine grained matrix (Fig. 4). The branching is perpendicular to the contact and the crystals generally curve inwards and downwards. Heterogeneous nucleation of these branching crystals is implied as their nucleation is related to rhomb-shaped feldspar phenocrysts in the matrix which are arranged parallel to the border, and occasionally reveal "flow" structures. Detailed study of these contact zones is currently being carried out as they may relate to physical conditions of the parental magma.

Similar branching crystal morphologies, referred to as comb-structure, have recently been reported from plutonic and subvolcanic rocks (e. g. Taubeneck & Poldervaart, 1969; Drewer & Johnston, 1972; Moore & Lockwood, 1973; Van Diver & Magetti, 1973) and are often found near the margins of intrusive bodies. Experiments show that such structures may generate as a result of substantial magmatic supercooling along a rapidly cooled margin (Lofgren & Donaldson, 1975).

The presence of contact zones showing metastable crystal morphologies strongly argues for a repeatedly intrusive origin of the lardalite massif, which can be regard-

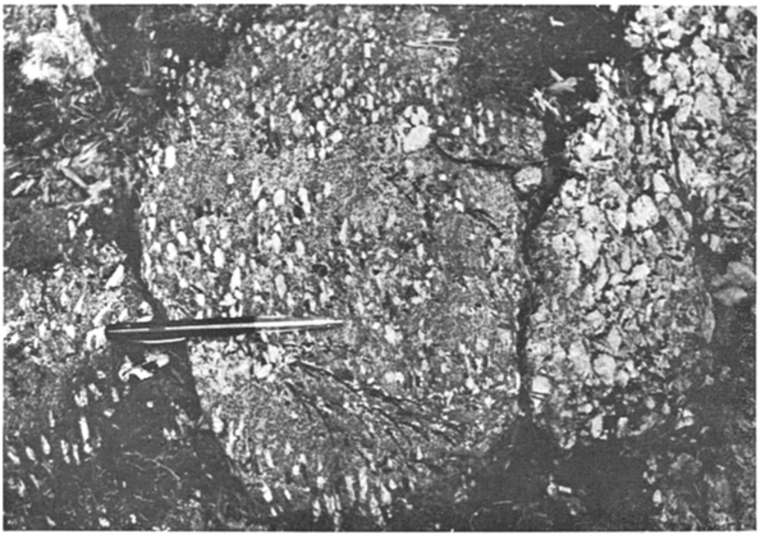

Fig. 4. Pyroxene dendrites in contact layer against coarse grained lardalite (right). Feldspar phenocrysts are orientated parallel to the border and provide nuclei for the growth of dendritic pyroxene, feldspar and nepheline. Occasionally the amounts of phenocrysts is low and the dendritic phases may form 20—30 % of the rock and single individuals reach more than 20 cm length.

ed as the core of the larvikite complex. The discovery of apparently similarly chilled larvikite variants also along other internal boundaries of the larvikite complex indicates an origin by multiple intrusion for at least part of the complex.

IV Magnetic Properties

Concentric patterns on the aeromagnetic maps of the Oslo-region have proved most helpful in the interpretation of the extent and shape of certain cauldrons and plutonic ring structures.

Total field aeromagnetic maps (N. G. U. 1971, 1973, 1974) have been used in this study and are particularly useful since several of the larvikite members show varying magnetic properties and thus allow distinction between some individual parts of the complex. The aeromagnetic maps reveal elongate anomalies which display circular patterns and are occasionally cut by other anomaly circle-arcs. These often possess different magnetic properties and thereby a pattern of moon-shaped anomaly-arcs is build up in a manner roughly similar to that observed from the structural data.

Generally the absolute magnetic field values for the larvikite vary between 50,000 and 51,000 gammas and the magnetic anomalies are mainly of a few hundred gammas within the individual anomaly-arcs. Locally, however, anomalies approaching 1,000 gammas are observed.

The nordmarkite which borders the northwestern part of the complex shows weaker magnetic properties than the larvikite, in accordance with a slightly lower normative content of magnetic and a more felsic character (BARTH, 1945). The magnetic field intensity clearly displays the circular boundary of this plutonic complex, which cross-cuts the more strongly magnetic larvikite field.

Within the larvikite area are found three roughly circular areas which show higher anomaly values. These are related to younger intrusive rocks of intermediate composition, previously cited as the hedrumite series (BRØGGER, 1898).

In addition to the moon-shaped anomaly-arcs found in the larvikite area relating to the structure of the complex, a regional variation in the magnetic field intensity is apparent. Generally, the NE part of the complex displays lower absolute field intensities than the SW part which might reflect different oxidation states in the evolution of the rocks. It is interesting that the larvikite in the NE part often contains hematite as a major oxide phase, whereas magnetite-ilmenite becomes an important constituent to the SW.

EVOLUTIONARY MODEL:

Structural composition

The present study of the larvikite massif in the southernmost Oslo-province seems to indicate that it is composite in origin and consists of numerous individual parts. The geometry of the arcs suggests a general shifting of centers towards the west and the structure of the larvikite complex therefore also implies a younging direction for igneous activity in this part of the Oslo rift-system.

The earliest phase according to this interpretation is to be found at Bolærne, which constitute a curved group of small islands and skerries in the central Oslofjord. This is cut by a new series of larvikite and tønsbergite, which appears immediately south of Tønsberg, suggesting a new center of activity roughly 10 km to the west.

The following larvikite arc is rather similar to the previous one in magnetic properties, but has a different composition, being quartz-free in contrast to the preceeding "tønsbergite"-types. The center has now shifted another 10—15 km towards the SW, and this process is continued for another set of arcs, so that the resulting width of the larvikite complex becomes more than 50 km, finally constituting about eight larvikite arcs and two lardalite masses.

Fig. (5) presents the distribution of suggested arcs in the southernmost larvikite massif. However, it should be stressed here that the positions of actual boundaries, and the total number of these, is based on reconnaissance mapping and existing available petrographic and geochemical data, in addition to the structural analysis of the region described here. It is evident that further detailed field studies in the area concentrating on the small mesoscopic differences between the individual members of the larvikite series may lead to slight adjustments of the presented patterns. The number of individual rings may be extended, since roughly concentric rings with similar magnetic properties and topographic effects will not be identified in this type of analysis.

It is possible that the location of fine grained porpyritic and subvolcanic varieties may facilitate this work, particularly since the reconnaissance mapping has revealed that these rocks sometimes occur at the boundary between certain larvikite arcs. Their origin as possible secondary ring dikes, as well as chilled margins should be carefully studied, and detailed petrographic analysis is obviously needed. However

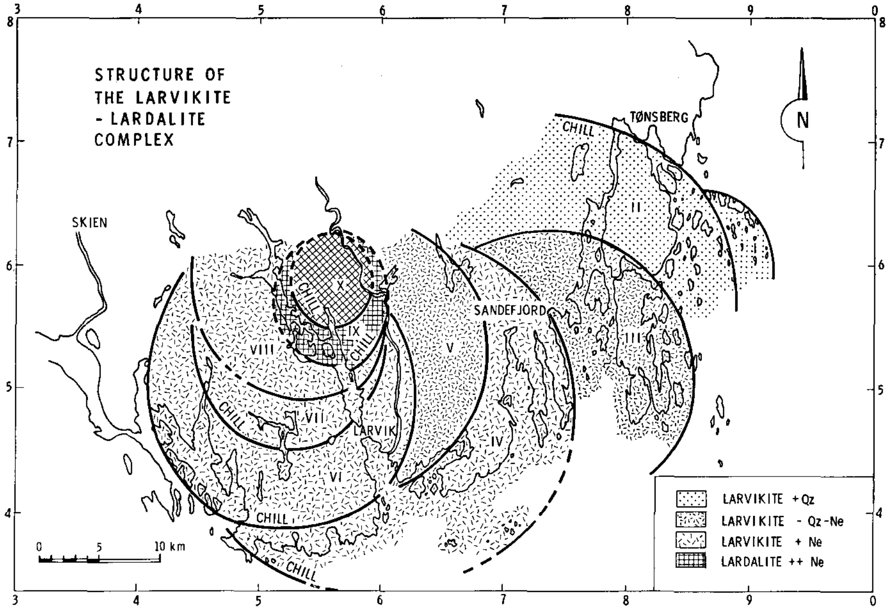

Fig. 5. Structural composition of the larvikite-lardalite complex. The larvikite segments suggest a systematic structural younging towards West and indicate a compositional variation ranging from early Qz-bearing varieties to late Ne-bearing types, including the lardalites which form the core of the complex. A general increase in undersaturation with evolution of the complex is implied.

the discovery of undoubtedly chilled rocks partly surrounding the lardalite massifs suggests that similar features may occur in the larvikite area and implies an origin as chilled margins for some of the subvolcanic larvikite varieties in the region. An origin of the complex by multiple injection is thus favoured.

Rock-type variations

Previous petrographic descriptions of larvikite in the southernmost Oslo-provinze include both Qz- and Ne-bearing varieties, as well as types which contain neither of these minerals (BARTH, 1944). A large number of samples from the larvikite massif have recently been collected during a regional U-Th study (RAADE, 1973). Petrographic study of these samples has revealed systematic and distinct variations within the larvikite complex; broadly stated the larvikite west of Farris contains excess nepheline, whereas most of that to the east of the Lågen valley contains neither free quartz nor nepheline, and finally, around Tønsberg, quartz is found in all thin sections (RAADE, 1973).

When plotted on the present map, the distribution of Qz- and Ne-bearing types clearly defines individual larvikite arcs. The area in which neither Qz nor Ne is in excess constitutes an intermediate type in an evolutionary series of larvikite from "primitive" variants, slightly oversaturated and containing quartz as a late interstitial phase, through the intermediate types to variants which contain interstitial and exsolved nepheline as the latest larvikite type. Two episodes of lardalite intrusion with excess nepheline between 10 and 40 % represent the final phase in the sequence.

Inverse zonation and the compositional variation of the lardalites suggest another mode of origin than simple differentiation from larvikite (JSP, in prep.). However a general trend towards a higher degree of undersaturation with magmatic evolution is maintained for these intrusives.

While the pattern may be more complex in detail than suggested here, the distribution of larvikite and lardalite occurrences can be explained in a manner that accounts for their apparently complicated internal variations.

The present study suggests that the areal distribution of larvikite is the result of a complex series of events and accordingly interpretations involving larvikite as a single unit may suffer from possible overlap between different evolutionary stages. Furthermore the individual larvikite centres may have acted as possible magmatic feeders and, as is the case with composite dikes, display considerable variation within a single section. Extremely complicated patterns would be result and regular regional variation of larvikite may thus be obliterated.

The larvikite series has often been cited as the plutonic equivalent of the rhomb-porphyries (Brøgger, 1933; Oftedahl, 1967) and as rhomb-porphyry transistions to larvikite are occasionally found within the larvikite complex, a correlation between the rhomb-porphyry series and the suggested larvikite sections is tempting. The occurence of plutonic rocks and their volcanic equivalents side by side, can be ascribed to their position in the rift-faulted environment.

Discussion

The structural pattern of the larvikite complex presented here suggests an evolution separated into several episodes which reflect slight displacement in their centers of activity. The formation of such patterns may be considered either as a result of complex cauldron subsidence, implying systematic displacement towards the WSW of zones of collapse, or indicate off-centered, multiple intrusion of larvikite masses which display regional variation towards higher degree of undersaturation with evolution of the complex. In either case the periodic evolution may be related to extrusive episodes in the region.

Since the larvikite complex covers almost the total width of the rift system, it forms a very important profile across the graben structure, and may provide information regarding the origin and evolution of igneous activity in this province, suggesting a unilateral younging towards the west. Such structures have not previously been reported from the southern part of the Oslo-province. However, similar geometrical patterns of structural younging can possibly be seen in the Nordmarka district, just north of Oslo (Sæther, 1962) where progressive younging northwards is suggested (see Fig. 1).

Systematic unilateral migration of volcanic centers across rift-zones been demonstrated from active oceanic rift-structures of Hawaii (Swanson et al., 1976), and suggest that the pattern observed in the larvikite massif may represent the root zones of a similar volcanic complex.

It has not yet been possible to determine whether these activity profiles represent considerably larger parts of the period of activity in the Oslo-provinces; however, they may represent two important activity vectors in any geometrical analysis of the evolution of the Oslo rift province, and suggest asymmetrical dilational opening of what could be regarded as a semi-rift system.

Acknowledgements

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Scapolite-bearing and related calc-silicate layers from the Alpujarride Series. (Betic Cordilleras of Southern Spain). A discussion on their origin and some comments

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With 7 figures and 2 tables

Zusammenfassung

Das häufige Auftreten von Kalksilikatbändern (manchmal mit Skapolith) in einigen alpujarriden Einheiten, besonders im zentralen und westlichen Abschnitt der betischen Kordillere, wird erklärt als Ergebnis einer metamorphen Differentiation von ursprünglich Ca-reichen Schichten. Die Anwesenheit von Skapolith legt eine hohe Anionenkonzentration der intergranularen fluiden Phasen während der Metamorphose nahe, bedingt durch evaporitisches Material der ursprünglichen Sedimente. Diese Hypothese, zusätzlich gestützt durch den extrem hohen Gehalt der umgebenden Pelite an löslichen Kathionen (Ca, Na, K), erlaubt die Korrelation der Kalksilikatbänder-haltigen Formationen mit aus anderen betischen Einheiten bekannten evaporitischen Serien des Permowerfenïan. Auf die stratigraphische Korrelation angewendet, legt dies nahe, daß öfters hochmetamorphe, permotriadische Serien fälschlicherweise als älter betrachtet wurden, was zu einer Unterschätzung der alpinen Metamorphose (Niederdruck—Hochtemperatur) im alpujarridem Bereich führte.

Abstract

Generalized development of calc-silicate bands in several alpujarride units of the central and western segments of the Betic Zone, is interpreted as the result of metamorphic differentiation from original calcium-rich sedimentary beds in the sequence. Presence of Scapolite suggests that this phenomenon may have been made possible by the catalizing action of high anion concentrations in the pore fluid medium during metamorphism, probably caused by the existence of evaporic material in the original sedi-

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