Isotope- and Trace-Element Chemistry, Geochronology

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Trace element chemistry

Trace element and isotopic studies of the Oslo igneous rocks are research topics initiated only recently and most of the data and their interpretations are still unpublished. Raade (1973) has investigated the distribution of the radioactive elements K, Th and U in the plutonic rocks, analyzing about 1000 samples from all over the Oslo Region. His major conclusion is that the plutonic rocks can be divided into two groups: (1) one with low and uniform Th/U ratios (averages between 3.5 and 4.5), including larvikite/kjelsåsite, lardalite, and related rocks; and (2) another group with higher and variable Th/U ratios (averages between 4.5 and 6.5), including nordmarkite (sensu stricto), ekerite and granite (see Table 1, which also includes published and unpublished data on lavas and Oslo-essexites).

The basaltic and rhomb-porphyry lavas have very similar Th/U ratios to those of the larvikites and related plutonic rocks of group 1. It is therefore reasonable to suggest that a genetic relationship exists between these rocks in that they have all retained a Th/U ratio which reflects that of a common parent magma. The rock-types that are characterized by cumulate phases, such as sørkedalite and the gabbros, show a slightly lower ratio than the lavas and other group 1 rocks, whereas rocks of a typical evolved nature (group 2), e. g. nordmarkite and ekerite, have considerably higher ratios. As both Th and U are incompatible elements the ratio should be preserved or only slightly modified during processes such as magmatic differentiation, which has been proposed for the rock series larvikite-nordmarkite-ekerite (Barth 1945a). The fact that the ratio changes markedly within this rock suite must signify either that other processes are involved or that the physical and/or chemical conditions have changed. Oxidation during magmatic differentiation has been proposed as a mechanism in the development of the evolved Oslo rocks (Czamanske & Mihálik 1972, Czamanske & Wones 1973), and U loss by oxidation is possible explanation for the observed changes.

Another important conclusion that can be drawn from the study of Th and U distributions is that large-scale modification of magmas by assimilation of country rock, especially of the Cambro-Silurian sediments, is far less common than previously assumed.

Weigand (1975) has studied the geochemistry of the basaltic lavas including the trace elements Cr, Ni, Rb, Sr, Th and U. He found that the basalts are

Table 1. Th/U ratios in Oslo igneous rocks

		Th/U mean	Std. dev.
Group 1: low and uniform ratios	Kjelsåsite and larvikite	3.63	0.42
	Akerite	3.85	1.12
	Sørkedalite	3.59	0.16
	Lardalite	3.72	0.10
	Pulaskite	3.94	0.81
	Grefsen syenite	4.39	0.62
	Foyaite	4.23	1.05
Group 2: higher and variable ratios	Nordmarkite	5.92	2.52
	Ekerite	5.47	1.46
	Granite	6.07	2.31
	Quartz porphyry	4.68	2.76
	Basaltic lavas¹)	3.88	0.93
	Rhomb-porphyry lavas²)	3.86	0.84
	Gabbros (Oslo-essexites)³)	3.40	0.40

¹) Data from Weigand (1975). ²) Unpubl. data from B. T. Larsen (1976). ³) Unpubl. data from S. Jacobsen, B. T. Larsen, E.-R. Neumann and B. Sundvoll (1977).

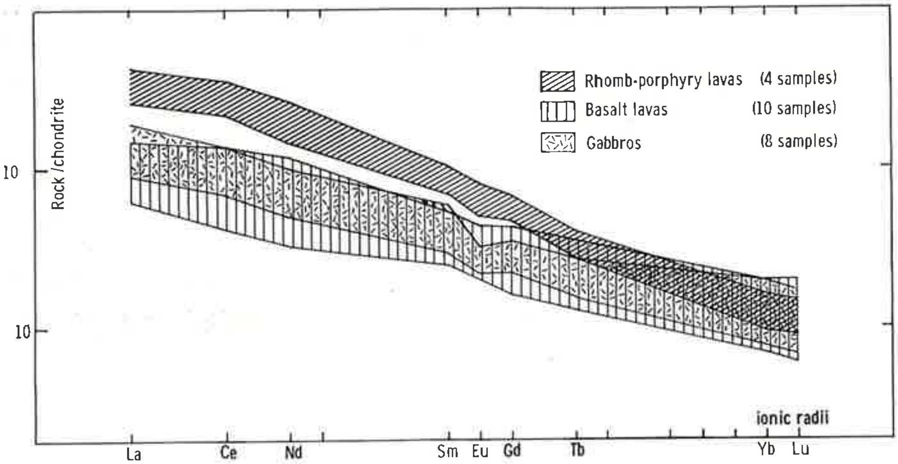

Fig. 1. Chondrite-normalized REE – distribution patterns of rhomb-porphyry lavas, basalts and gabbros from the Oslo rift. Data from Finstad (1972), ORP–13 and OE–13 excluded.

composed of at least two groups easily divisible on the basis of their trace element contents: a tholeiitic group (of continental plateau type) characterized by low Rb, Sr, Th and U contents and uniform Cr and Ni values; and an alkali-olivine basaltic group (including hawaiite and mugearite differentiates) with higher Rb, Sr, Th and U and variable Cr and Ni contents. Investigations in progress by this author, and also shown by Segalstad (1976), have revealed the existence of a third group of basalts made up of basanites and other silica-undersaturated types. These are even more enriched in the above elements, especially Sr, Th and U (Weigand 1975, Table 7, columns 1 and 5–10). The relationship between these three groups of basalts is tentatively considered by the present author to be one in which the lava types are derived from different partial melts of a common upper mantle magma source.

Finstad (1972) has briefly investigated the relationship between the basalts and the gabbros, and the basalts and the rhomb-porphyry (RP) lavas, using REE distributions; his results are presented in Fig. 1. The chondrite-normalized pattern of the gabbros is closely matching the basalt pattern but for the presence of negative Eu-anomalies in the former due to the mafic cumulate members of this group of rocks. The difference in shape of the REE pattern of the RP-lavas and the basalts is, for the most part, caused by the tholeiite members. These have considerably lower contents of light REE and corresponding higher contents of heavy rare-earths than the alkali-olivine basalts and the basanites. The average increase in REE concentration in the RP-lavas compared with the alkali-olivine basalts is 2.2 (La) to 1.9 (Lu), and may suggest a common source in a parent magma with this same REE-distribution pattern (La/Lu $\sim$ 180–210).

Most workers on Oslo igneous rocks from Brøgger and onward (Barth 1945a, Holtedahl 1953, Oftedahl 1960) have agreed on the model of a differentiation series, kjelsåsite/larvikite-nordmarkite-ekerite; Sæther (1962) and Raade (1973), on the other hand, consider that the larvikite has no direct relationship with the rest. Field evidence, major element chemistry and mineralogy do, however, support a close genetic relationship between the nordmarkites (sensu stricto) and the ekerites. Dietrich et al. (1965) and Dietrich & Heier (1965) also found a marked enrichment of the trace elements Li, Be, Rb, Zr, Nb, Cs, Tl and Pb and a corresponding depletion of V, Sr, Ba, La and Nd with fractionation index, going from nordmarkite to ekerite. In some cases, however, the enrichment and corresponding depletion of these elements are not uniform, suggesting that effects of a volatile phase must also be considered.

Isotope chemistry

Isotopic data on the Oslo igneous rocks are sparse and are summarized by Heier & Compston (1969). Lead isotopes have been reported by Faul et al. (1959) and Moorbath & Vokes (1963). The precision of these analysis is rather poor by present-day standards and only a restricted amount of information can be extracted from them.

Lead from within the igneous rocks and in deposits in the nearest contact aureole around them appears to be of normal type, yielding concordia ages of the expected magnitudes (240–265 mill. years) and $^{238}U/^{204}Pb$ ratios which are in agreement with a continental magmatic province of a single source origin (9.0–9.3).

Strontium isotopes have been reported by Heier & Compston (1969) and Jacobsen & Raade (1975). Heier & Compston have analyzed 28 rock samples of different plutonic rock-types and found that, with the exception of the

Table 2. Rb/Sr-whole rock-isochron ages of individual igneous bodies

	Isochron age[1]) (mill.y.)	$^{87}Sr/^{86}Sr$ initial ratio
Lake Eikern ekerite	275 ± 5	0.7064 ± 0.0018
Siljan nordmarkite	278 ± 7	0.7042 ± 0.0002
Vestfold larvikite/lardalite	271	0.7041 (errorchron)
Drammen biotite granite	284 ± 13	0.7033 ± 0.0011
Nordagutu biotite granite	284 ± 7	0.7044 ± 0.0002

[1]) $\lambda^{87}Rb = 1.39 \cdot 10^{-11}\ y^{-1}$

Drammen biotite granite samples and 3 'abnormal' ekerite samples, they define a single isochron with an initial $^{87}Sr/^{86}Sr$ ratio of 0.7041 ± 0.0002 (2σ). This, they concluded, is best interpreted as indicating the presence of a comagmatic suite originating from a magma in the upper mantle, and that the rocks most probably are related by magmatic differentiation rather than differential melting in the source region.

In their investigation Heier & Compston (1969) have not differentiated between samples from quite dissimilar petrographic rock-types for which the true relationship is by no means clear, as in the case of the lardalites and the larvikites or between the biotite granites and the other plutons. Moreover, they have also sampled from unquestionably different plutons and this, combined with a rather modest precision in the Sr-isotopic analysis, suggests that small but real differences in ages and initial Sr-isotopic ratios might be concealed by the extreme spread in Rb/Sr-ratios (0.03–70!). Regrouping the data according to petrographic rock-type and geographic locality, i. e. into individual massifs or bodies, shows that the bulk of the samples is from four large plutons all in the southern part of the Oslo Region. Thus, individual isochrons can be constructed for these four, more or less homogeneous and coherent bodies. The results of such a refit of the data from Heier & Compston are given in Table 2 together with the data on the Nordagutu biotite granite from Jacobsen & Raade (1975).

The spread in ages is certainly not significant, but the initial $^{87}Sr/^{86}Sr$ ratio of the ekerite body is decidedly higher than the others. The reason for this will not be discussed further here, but it does indicate that the Sr-isotopes in the Oslo igneous rocks are more complex than apparent from previous work.

New and hitherto unpublished data on the Rb/Sr relationship of the Oslo igneous rocks obtained by the author tend to confirm this. In the intermediate to acidic and silica-undersaturated group of plutonic rocks the $^{87}Sr/^{86}Sr$ initial ratios vary between 0.7038 and 0.7073. In the basic rocks (basalts and gabbros) the measured Sr-isotopic ratios range between 0.7037 and 0.7078. Corrections for age are in some cases difficult to apply due to alteration, but initial ratios in the range 0.7034 to 0.7053 are considered to be valid. This shows that all the Oslo igneous rocks, including the biotite granites, have very similar and comparably low initial $^{87}Sr/^{86}Sr$ ratios, thus strengthening the theory of a common upper mantle magma origin.

No work on stable isotops has so far been carried out on the Oslo igneous rocks.

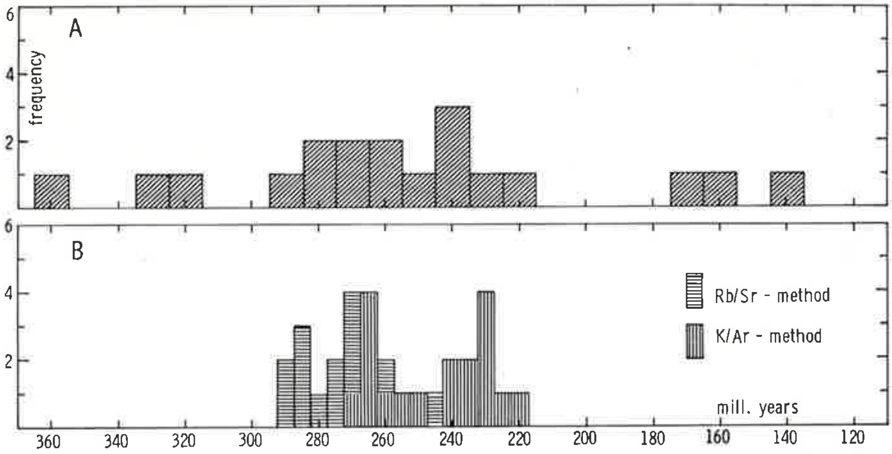

Fig. 2. A. Frequency distribution of age determinations reported by Neumann (1960), Moorbath & Vokes (1963) and Heier & Compston (1969). Resolution = 10 mill. years. B. Frequency distribution of age determinations reported by Jacobsen & Raade (1975), Ineson et al. (1975), Larsen (1975), and unpublished data from the author. Resolution = 5 mill. years.

Radiometric age determinations

Finds of fossils in the concordant sequence of sediments occurring just below and also in between the lava flows of the lowermost basalt unit (B_1) have been reported as indicating a Lower Permian age for these strata (see Henningsmoen, this volume), and that consequently the igneous rocks and the tectonic structure should be contemporaneous and/or younger. The palaeontological indications are, however, not entirely conclusive.

Radiometric age determinations carried out by different methods up to 1960 were summarized by Neumann (1960) and Moorbath & Vokes (1963). A number of determinations are obviously of very poor quality and are not discussed here. The spread in ages ranges from 355 to 136 mill. years, although most of them are between 280 and 240 mill. years (Fig. 2a). All workers have stressed the discordant nature of their data and that they should be taken as minimum ages.

The more recent investigation by Heier & Compston (1969) noted above yielded a single whole rock Rb/Sr isochron age of 276 ± 2 mill. years for the whole suite of plutonic rocks, the Drammen biotite granite excluded. These authors therefore concluded that the plutonic activity occurred over a remarkably short time span (<3–4 mill. years). A brief time span for the igneous activity has also been stressed by Oftedahl (1967) in his studies of the lavas. Field evidence on the contact relationships between different rock-types and bodies have also been interpreted as providing support for such a conclusion, although Sæther (1962) was clearly aware of the time needed to cool down huge plutonic bodies. The concept of a short time span for the formation and development of the Oslo rift is, however, even more remarkable when compared with other rift structures such as the Ethiopia or Kenya rifts where the magmatic activity has covered periods of at least 10–20 mill. years and is still going on.

For the reason outlined in the previous section, the work of Heier & Compston is ambiguous and their age determination therefore inconclusive. The more recent age determinations of Oslo rocks would, in fact, seem to require modifications of the hitherto prevalent 'short time span' view (Jacobsen & Raade 1975, Ineson et al. 1975, Larsen 1975a, and unpublished data by the present author), in that the magmatic activity has a span of at least some ten million years and with no single event-cluster visible in the data (Fig. 2b).

The K/Ar data reported by Ineson et al. are subject to criticism because or their discordant nature, but the persistence of values around 230 and 265 mill. years are, in this author's opinion, significant, and seen in conjunction with the new Rb/Sr data they indicate a magmatic activity in the Oslo rift throughout the whole of the Permian period.

Although it is premature to draw any safe conclusions on the individual ages reported so far, it is interesting to note that the biotite granites of Drammen and Nordagutu (Table 2), previously thought to be very late, end products in the Oslo igneous suite, now appear to belong to the earliest intrusions, an observation which makes their questionable position in this suite even more doubtful.

It is also interesting to note the increasing radiometric and palaeomagnetic age evidence for contemporaneous and most probably co-magmatic igneous activity outside the Oslo Region proper. Examples of this include the basic dykes and plugs in the Precambrian of southern Norway (Halvorsen 1970, Touret 1970), basic dykes in south-western Sweden (Mulder 1971), nordmarkite and larvikitic rocks from borehols in Denmark (O. Larsen 1971) and, most recently, the Särna alkaline complex in western Sweden (Bylund & Patchett 1977).