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MASS ESTIMATES OF CUMULATES AND RESIDUES AFTER ANATEXIS IN THE OSLO GRABEN

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Abstract. The magmatic province of the Permian Oslo Rift, southeast Norway, is dominated by rocks of monzonitic to granitic composition. Most of the monzonitic rocks are believed to have formed by fractional crystallization from mantle-derived magmas, whereas melts produced by anatexis in the lower crust are important to the formation of the syenitic and granitic rocks. These processes have left dense cumulates and dense residues after melting in the crust. The surplus masses of cumulates and residues at depth in the crust can be estimated by using petrological and geological information on the rocks exposed today. Quantitative estimates for the Oslo Graben are comparable to corresponding data derived from geophysical crustal models. The petrological/geological estimates suggest excess masses of 7-10x10^{10} kg per linear meter (assuming prismatic bodies) along the rift axis in the southern, and 5-7x10^{10} kg/m in the northern part of the Oslo Region. These estimates are dependent upon the volume proportion of trapped liquid in the cumulates, and the ratio of cumulates to residues after anatectic melting in the crust; the amount of trapped liquid appears to be low (less than 25%). The results agree well with estimates by Wessel and Husebye (1986) of excess mass in the crust based on gravimetric data, which gave 5-7x10^{10} kg/m. This agreement testifies to the validity of making mass estimates on the basis of petrological and geological data. The data bear on the composition and evolution of the upper lithosphere in the graben area; some cumulates may reside in the subgraben mantle.

Introduction

The Oslo Region alkaline province in southeast Norway (Figure 1) formed during a continental rifting episode in Permo-Carboniferous time. Extrusive and intrusive rocks cover about 6500 km^2 of the rift floor. About 96% of this area exhibits monzonitic (larvikite and rhomb porphyry) to granitic (ekerite, alkali granite, and biotite granite) rock types, whereas basalts and gabbros only cover 4% [Ramberg, 1976]. Also most of the basalts and gabbros have a somewhat evolved character [Neumann et al., 1985]. The large volumes of felsic rocks in the Oslo Region were earlier believed to be derived by partial fusion in the deep crust [e.g., Barth, 1954; Oftedahl, 1952, 1967]. More recent studies have concluded that at least some of these rocks originate from mantle-derived magmas by fractional crystallization [Neumann, 1978, 1980; Neumann et al., 1985; Ramberg, 1976; Sundvoll, 1978].

The production of large volumes of felsic rocks by either crustal anatexis, or by fractional crystallization from mantle-derived mafic magmas, implies the existence of large masses of dense residues or dense cumulates in the crust. The supposed existence of such rocks is supported by gravimetric data [Ramberg, 1976; Wessel, 1984; Wessel and Husebye, 1986] and appears to have a seismic counterpart as well [Gundem, 1984]. Geophysical crustal models along with a sketch of petrogenetical processes are outlined in Figure 2.

The aim of this paper is to estimate surplus masses of the Oslo Graben cumulates and dense residues by means of studies on rocks exposed today. These estimates will be compared with corresponding data derived from geophysical crustal models. Since geophysical rift parameters tend to fade with age, such a comparison may prove to be useful and will be used to discuss the composition and evolution of the upper lithosphere in the graben area.

A proper starting point will be to derive equations for excess masses produced by cumulates and residues. Data from geophysical and geochemical models for the Oslo Graben will then be presented along with volume estimates of felsic rocks. Finally, results are presented and discussed with reference to the northern and southern parts of the graben, respectively.

Method for Estimating Mass of Cumulates

Cumulates with a positive density contrast vis-à-vis the surrounding crust will represent an excess mass in the crust. Our aim is to derive expressions whereby excess mass caused by cumulates is related to geochemical and physical parameters measurable in surface rocks or alternatively estimated on the basis of petrogenetic modeling. A sketch of these methods, together with a list of indices used in equations for excess masses, is presented in Figure 3.

The excess mass (ΔM_{Cr}) is the difference between the mass (M_{CR}) of a given volume (V_{CR}) of cumulate rocks deposited in the crust, and the mass (M_P) of the same volume of crustal rocks (V_{Cr}) before emplacement of the cumulates.

$$\Delta M_{Cr} = M_{CR} - M_P = M_{CR} - V_{Cr}\,\rho_P \qquad (1)$$

where ρ is density.

A cumulate consists of cumulate crystals (C) plus intercumulus material (RI) crystallized from trapped liquid.

$$M_{CR} = M_C + M_{RI} \qquad (2)$$

$$V_{CR} = V_C + V_{RI} \qquad (3)$$

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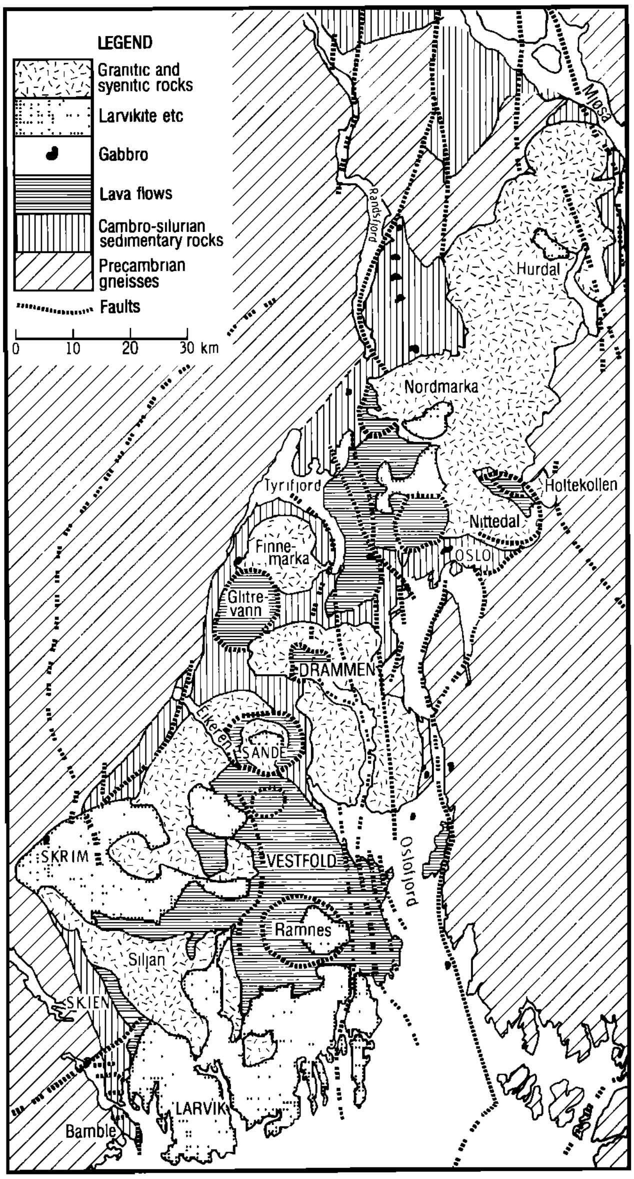

Fig. 1a. Generalized geological map of the Oslo Region showing the locations and surface extents of the lavas, and monzonitic and granitic intrusive bodies discussed in the text. Based on maps by Oftedahl [1960] and Ramberg and Larsen [1978].

The intercumulus material may take the form of (1) new minerals nucleated within the intercumulus liquid, (2) further growth on the cumulus phases, and/or (3) reaction replacement of cumulus crystals. The volume fraction of intercumulus material in a cumulate varies considerably. Estimates, based partly on studies of natural cumulates, partly on porosity in packing experiments, range from 0.06 (6%) to 0.50 (50%) [Cox et al., 1979]. The relative amount and form of the intercumulus material will, of course, greatly influence the physical properties of the cumulate. The volume proportion of intercumulus material in the cumulate rock is R; consequently;

$$V_C = V_{RI}(1-R)/R \qquad (4)$$

As per definition, V_{CR} is equal to V_{Cr}; we may substitute the above information to rewrite expression (1):

$$\Delta M_{Cr} = M_C + M_{RI} - V_{RI}\,\rho_p/R \qquad (5)$$

The mass or volume of interstitial material or cumulus minerals in a cumulate in the intermediate or deep crust cannot be measured directly but can, through petrogenetic modeling, be tied to masses of residual melts crystallized at or near the surface.

Removal of minerals (M_C) from a primary melt (mass M_{PM}) gives a mass fraction (F) of residual liquid (M_R). One part of this residual liquid (M_R) crystallizes as intercumulus material (M_{RI}); the other part of the liquid intrudes the upper crust and crystallizes there (M_{RU}). The volume of this last rock (V_{RU}) constitutes the basis for the following estimates of cumulate masses. The mass ratio (K) of cumulus minerals to residual liquid is

$$K = M_C/M_R = (1-F)/F \qquad (6)$$

and

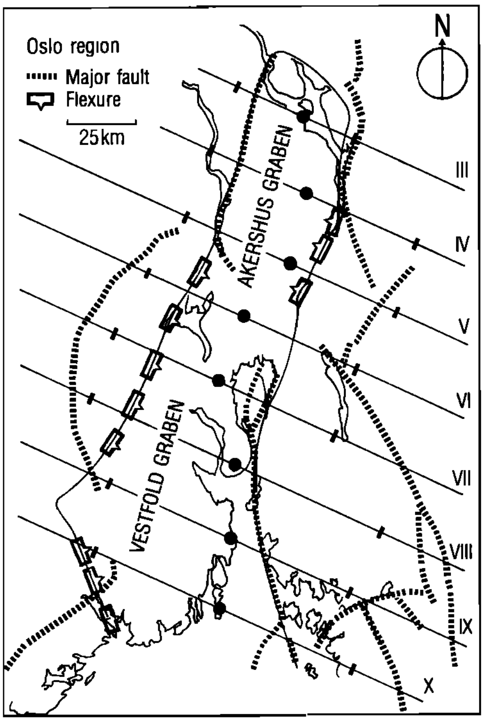

Fig. 1b. Sketch map showing the division of the Oslo Region into two graben segments, the Vestfold Graben and the Akershus Graben, as suggested by Ramberg and Larsen [1978], and the positions (III through X) of the geophysical profiles used in the gravity interpretations discussed. The lateral extents and centers of the anomalous mass in the crust, as defined by Wessel [1984] and Wessel and Husebye [1986], are indicated by the tickmarks and solid circles, respectively.

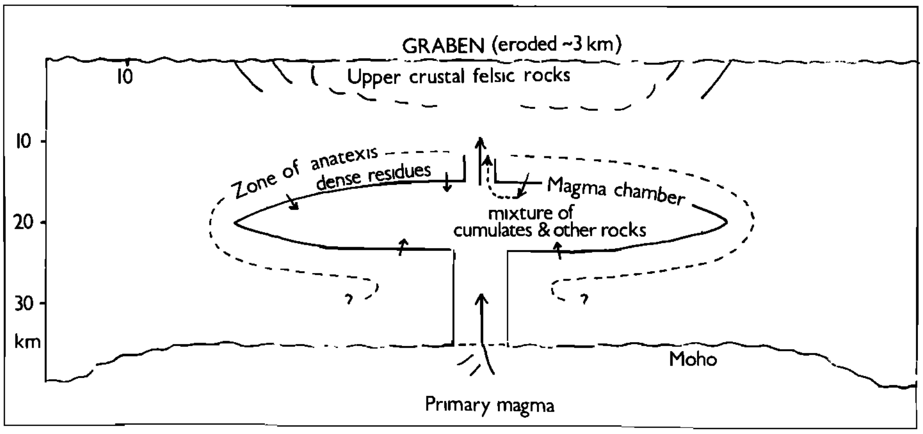

Fig. 2a. Schematic presentation of processes operating in the crust during the rifting event, and the mass transport they caused. The illustration is meant to account for the midcrustal surplus masses shown by gravity and seismological models (see text) only; several possibilities exist for the structural evolution of the lower crust. The figure presents a single midcrustal magma chamber. Geochemical data, however, imply that a number of isolated, or semi-isolated, magma chambers must have existed at any given time during the active lifetime of the rift.

$$M_C = K\,M_R = K\,(V_{RI}\rho_{RI} + M_{RU}) \quad (7)$$

By inserting (4) for V_{RI}, M_C/ρ_C for V_C, and rearranging, we get

$$M_C = M_{RU}\,K\,\rho_C(1 - R)/[\rho_C(1 - R)-\rho_{RI}K\,R] \quad (8)$$

where

$$\rho_C = (\rho_C^I\,V_C^I + \rho_C^{II}\,V_C^{II} + \ldots)/V_C \quad (9)$$

and

$$V_C = V_C^I + V_C^{II} + \ldots \quad (10)$$

where I, II, etc., signify different cumulus mineral assemblages and ρ_C and ρ_{RI} are the densities of the cumulus and intercumulus material, respectively. Densities must be corrected for pressure and temperature at the relevant crustal depth; this implies a need for data on the thermal state of the crust plus mineral compressibility and thermal expansion coefficients.

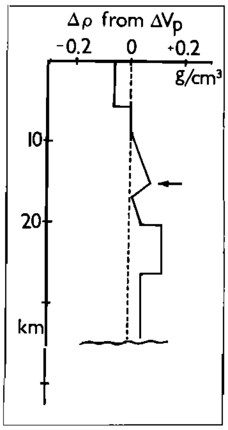

Fig. 2b. Lateral density contrasts of graben calculated from seismic velocity distribution given by Gundem [1984]. The arrow marks level of the Conrad discontinuity found outside the graben only.

We may now rewrite (5) for excess mass:

$$\Delta M_{Cr} = M_{RU}\,K[(1-R)\rho_C + R\,\rho_{RI} - \rho_P]/[(1-R)\rho_C - K\,R\,\rho_{RI}] \quad (11)$$

We assume that the cumulates form approximate prismatic blocks in the crust. Then the excess mass per unit length of the graben is

$$\Delta M'_{Cr} = \Delta M_{Cr}/L_{Cr}$$

or

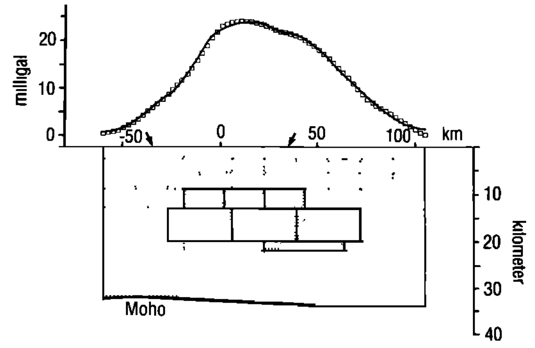

Fig. 2c. Lateral density contrasts in the graben calculated from gravity anomalies (in mgals) for profile XI in Figure 1 [redrawn from Wessel and Husebye, 1986]. The fully drawn hatched prisms have density contrasts of 0.06 g/cm^3 to the side rock. Density contrasts for the nonhatched prisms are in the range from -0.02 to +0.02 g/cm^3 (not significant). The width of the graben is indicated by arrows.

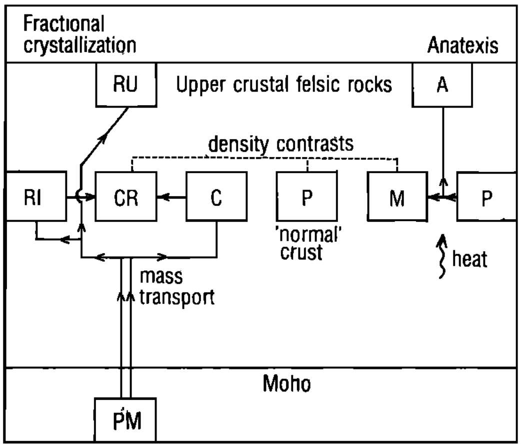

Fig. 3. A schematic illustration of the model used to calculate surplus masses from petrological data. Symbols used here and in the text are PM, primary magma from the mantle; CR, cumulate rock consisting of C, cumulus phases, and RI, intercumulus material (or "trapped liquid"); RU, magmatic rocks of mantle origin in upper crust; P, normal country rock at a given level (in the Oslo rift, these are Precambrian); A, magmatic rocks of crustal origin in the upper crust; and M, mafic residues after melting.

$$\Delta M'_{Cr} = M_{RU} K [(1-R)\rho_C + R \rho_{RI} - \rho_P]/ [(1-R)\rho_C - K R \rho_{RI}]L_{Cr} \qquad (12)$$

where L_{Cr} is the block length measured along the rift axis.

Qantitative estimates of ΔM_{Cr} also require (1) data on the volumes of surface or subsurface rocks representing residual melts (V_{RU}), and (2) pressure and temperature dependent estimates of densities of the relevant cumulus phases. Estimates of these parameters are presented below. The density of the intercumulus material (ρ_{RI}) will, depending on its composition (see discussion above), vary between ρ_C and ρ_{RU}, the latter representing the density of the rock crystallized from the residual melt.

Method for Estimating Mass of Residues after Anatectic Melting

Another factor of importance is anatectic melting, which will result in positive gravity anomalies by leaving dense residues in the crust. Such a process will produce a melt dominated by feldspar and quartz components with compositions in the range granite-granodiorite. A residue enriched in relatively dense minerals such as plagioclase and mafic silicates is left in the melt region, and the melting process frequently includes dehydration and reactions to form new mineral assemblages [e.g., Wyllie, 1977].

The mass of the dense residue (M_M) is

$$M_M = M_P - M_A \qquad (13)$$

where M_P is the mass of crustal rock subjected to partial melting and M_A is the mass of rock crystallized from the anatectic melt.

The degree of melting D may be expressed as

$$D = M_A/M_P \text{ or } M_P = M_A/D \qquad (14)$$

The dense residue will (locally) represent an excess mass (ΔM_M) in the crust as compared with the situation before anatexis occurred:

$$\Delta M_M = V_M(\rho_M-\rho_P)$$

or

$$\Delta M_M = M_M(\rho_M- \rho_P)/\rho_M \qquad (15)$$

We combine (13), (14), and (15) and get

$$\Delta M_M = M_A \, (1-D)(\rho_M-\rho_P)/D\rho_M \qquad (16)$$

$$\Delta M'_M = M_A(1-D)(\rho_M-\rho_P)/D\rho_M L_{Cr} \qquad (17)$$

where L_{Cr} is the length of the crustal segment affected by anatexis.

Unfortunately, details on the anatectic melting processes, such as data on ρ_M and D, are lacking, thus impairing quantitative estimates of excess mass in the crust after anatectic melting. However, some assumptions can be made in order to estimate the magnitude of these parameters, and this problem will be adressed below. Assuming that there are no phase changes produced by the melting process, this entails that both the rock formed from the anatectic melt and the residue consist of mineral phases found in the initial rock. We then have

$$V_P = V_M + V_A \qquad (18)$$

The above equations may also be used to express the relationship between densities and degree of melting:

$$\rho_M = \rho_P\rho_A \, (1-D)/(\rho_A-D\rho_P) \qquad (19)$$

Combining (17) and (19), we get a relation for excess mass per unit length of a graben segment:

$$\Delta M'_M = M_A \, (\rho_P - \rho_A)/\rho_A L_{Cr} \qquad (20)$$

In other words, given that the basic assumptions are valid, we need only to know the mass of the felsic rocks produced from the anatectic melt, the densities of the initial and anatectic rocks, and the length of the graben segment in question.

The geochemical data available imply that the anatectic melts produced in the Oslo Region had a syenitic composition and thus gave rise to K_2O-rich nordmarkites (E. Rasmussen et al., unpublished manuscript, 1986). Setting ρ_A = 2.62 g/cm^3 for nordmarkites inside the graben (Table 1) and ρ_P = 2.83 g/cm^3 for Precambrian rocks outside the graben, the excess mass becomes

$$M'_M = 0.080 \, M_A/L_{Cr} \qquad (21)$$

Geophysical models for the Oslo Graben and adjacent areas

The geophysical models presented below give information on intracrustal density distributions

TABLE 1. Densities and Estimated Volumes and Masses of Felsic Rocks in Different Parts of the Oslo Graben

	Mean Density 10^3 kg/m^3	Volume 10^9 m^3	Mass 10^{14} kg	Genetic Origin
Akershus Graben, central Oslo Region				
Nordmarka-Hurdal syenite complex	2.62	9,809†	257.0†	Mixed
Finnemarka granite	2.62	336†	8.8†	Unknown
Rhomb porphyry lavas	2.72	75*	2.1	Mantle
Southern Vestfold Graben				
Glitrevann central pluton	2.61	336†	6.1†	Unknown
Drammen granite	2.61	1,811†	47.3†	Unknown
Eikeren-Skrim granite	2.61	1,376†	35.9†	Unknown
Siljan syenite	2.62	256†	6.7†	Unknown
Larvik-Skrim larvikite	2.71	10,000*	271	Mantle
Sande central pluton	2.65	83†	2.2	Mixed
Ramnes central pluton	2.67	139†	3.5†	Mixed
Rhomb porphyry lavas	2.72	100*	2.7	Mantle

The assumed origin is indicated in the last column: mantle, derivation by fractional crystallization from a mantle-derived primary melt; mixed, derivation by mixing between anatectic and mantle-derived melts.

*Oftedahl [1952].

†Ramberg [1976].

and thermal state today and will be used in modeling and discussion.

Gravimetric Data

The result of an extensive gravity study was published by Ramberg in 1976. By subtracting a regional field calculated from variations in Moho depths from a smoothed version of the observed (Bouguer) field (corrected for outcropping light rocks), he found a broad residual gravity high of about 20-25 mgal along the entire rift zone. He concluded that this gravity anomaly reflects large volumes of dense rocks (mafic to ultramafic cumulates) predominantly in the lower crust. The deep crust alternative (favored by Ramberg) gave an estimated total mass of the dense body of about 3.75×10^{17} kg, and volume of about 120,000 km^3 assuming a density contrast of 0.1 g/cm^3 to side rocks of "normal" densities.

The Oslo Region gravity anomalies have recently been reinterpreted by means of inverse methods, including options for imposing constraints by incorporating seismological

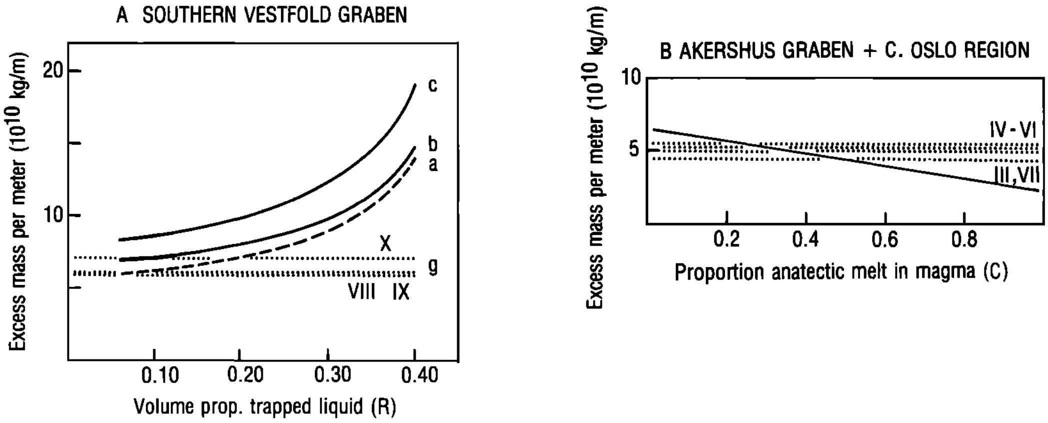

Fig. 4. Excess mass per meter along the rift axis as estimated from petrological/geological data (solid lines) as a function of the volume proportion of trapped liquid in cumulates (R) for the southern Vestfold Graben; and the proportion of anatectic melt in the magma (C) for the Akershus Graben and central Oslo Region. A detailed discussion of the calculation methods and the significance of the lines a, b, and c are given in the text. Dotted lines represent excess mass per meter as estimated from the gravity inversion of Wessel and Husebye [1986]. Roman numerals refer to profiles III to IX in Figure 1.

results [Wessel, 1984; Wessel and Husebye, 1986]. These methods give less ambiguous results than older ones with respect to the location in the crust of anomalous bodies, and their density contrasts to the surrounding rocks. Wessel's density inversions place a slightly asymetrical body in the intermediate crust (between 6-9 and 22-27 km depth), as illustrated in Figure 2. The body is 46 to 116 km wide and extends under the flanks of the rift, particularly eastward. The average density contrast to the side rock is 0.06 g/cm^3. The normal density overlay was calculated for each profile by means of a modified version of Birch's law (se below). The size of the anomalous body in cross section and the excess mass per meter along the rift axis relative to the side rock have been estimated from Wessel's data and range from 4.5 to 5.6x10^{10} kg/m in the northern and central part of the graben (profiles III to VII in Figure 1b) and from 5.9 to 7.1x10^{10} kg/m in its southern part (profiles VIII to X; see also Figure 4).

Seismological Data

Recent information about the structure of the crust in the Oslo Graben and adjacent Precambrian terrain has been obtained through seismic reflection and refraction data [Gundem, 1984; see also Tryti and Sellevoll, 1977] based on NORSAR array recordings. Gundem's velocity profiles of the graben and normal crust near Oslo have been converted into a density contrast profile (Figure 2) by using a modified version of the original Birch's [1961] law relating density (ρ) and P velocity (α) in the crust ($\rho(\alpha) = 0.572 + 0.355\alpha$). In spite of somewhat poor resolution, Gundem [1984] concludes that the presence of velocity gradients and high seismic velocities in the intermediate crust (10-20 km) agrees well with Wessel's [1984] model of a dense body in roughly the same area.

Thermal Model

The thermal anomaly connected with the rifting and its associated magmatism have now ceased; at the surface, no significant heat flow anomalies have been recorded. Interpretations of heat flow measurements imply temperatures below the graben of about 200°C at 15-km depth and 350°C in the Moho region (30-35 km) [Haenel et al., 1979]. This thermal model will be used below to correct densities for thermal expansion and compressibility.

Geochemical Model for the Oslo Rift

Recent interpretations of a wide range of petrological and geochemical data on felsic Oslo Graben rocks strongly suggest the following evolutionary model [Neumann, 1980; Andersen, 1984; Rasmussen, 1983; E. Rasmussen et al., unpublished manuscript, 1986].

1. Most larvikites (including those in the Larvik pluton) and rhomb porphyry (RP) lavas are formed from mantle-derived mafic magmas by fractional crystallization in the lower or intermediate crust.
2. Some nordmarkites (alkali syenites) represent crustal anatectic melts.
3. The majority of syenites and granites are formed as the result of mixing between mantle-derived and anatectic melts, followed by fractional crystallization.

Possible fractionation models were tested by computer simulation of fractional crystallization on the basis of published experimental data on mineral-melt equilibria (for details, see Andresen [1985]). The models tested involve the phases olivine, clinopyroxene, plagioclase, and Fe-Ti oxides. The relative proportion of each phase involved in each crystallization stage was chosen on the basis of experimental data on natural and simplified systems [Cox and Bell, 1972; Presnall et al., 1978] . At the start of these calculations, the primary magma composition was taken from a paper by Neumann et al. [1985] and checked against compositions suggested in the Basalt Volcanism Study Project [1981]. These initial compositions were subsequently adjusted through an iteration process to fit the chemical character of the different Oslo Graben rock series. Gundem's [1984] and Wessel's [1984] geophysical models imply that cumulates make up part of the crust between about 8 and 22 km (or about 2.2 and 6.2 kbar, respectively). Crystallization in the intermediate crust (about 15 km or about 4 kbar) is therefore chosen as the basis for the crystallization model presented below.

The best fit between a calculated residual melt and the least evolved larvikite magma (lowest rhomb-porphyry unit (RP_1) at Krokskogen) was obtained on the basis of stages I-III (F=0.45) of the model presented in Table 2.

These results imply that the production of larvikitic magmas resulted in olivine-clinopyroxene rich cumulates at some depth in the crust.

Although petrological data indicate that plagioclase started to crystallize before intrusion of larvikitic magma into the upper crust [Neumann, 1980], our simulations indicate that unless the primary magma was anomalously rich in Al_2O_3 and Na_2O, removal of plagioclase at depth cannot have been significant. An additional crystallization step (stage IV; Table 2) leads from the least to the most evolved larvikites [Neumann, 1980]. Continued removal of assemblage IV may produce syenitic and granitic residual melts.

Volumes of Felsic Rocks

In most of the Oslo rift, erosion has cut through the pre-Permian surface and into the Permian batholiths (Figure 1). The existing volumes of surface and subsurface felsic rocks are thus clearly smaller than the original volumes of such rocks and will, when used to estimate the masses of dense cumulates, give minimum values. The estimates of rock volumes used in the excess mass estimates are listed in Table 1, together with densities measured by Ramberg [1976], and calculated masses.

Granitic rocks in the Oslo Region have a negative density contrast to the side rocks. Ramberg [1976] could therefore estimate the volumes of the granitic batholiths on the basis of gravity observations; the essence is that the granitic intrusions extend to 4-12 km below the present surface.

TABLE 2. Model of Fractional Crystallization

Stage	F	Crystallizing Assemblage
I	1.0 - 0.9	ol
II	0.9 - 0.7	ol_{20} cpx_{80}
III	0.7 - 0.45	ol_{18} cpx_{77} mt_5
IV	0.45 - 0.27	ol_8 $plag_{86}$ mt_4 ap_2

F, mass ratio of residual to original magmatic liquids; ol, olivine; cpx, clinopyroxene; mt, TiO_2-rich magnetite; plag, plagioclase; and ap, apatite.

The larvikites have no density contrast to the side rocks. Their volume thus cannot be estimated on the basis of gravity measurements. Oftedahl [1952] estimated the total volume of the Larvik and Skrim larvikite batholiths to be about 10,000 km^3 on the basis of the areal extent of about 2000 km^2 and an assumed depth of 5 km. A homogeneous vertical section of about 800 m is exposed. The lavas cover an area of about 1500 km^2 and have today a volume of about 500 km^3, of which about 55% are basalts, 35% rhomb porphyries (175 km^3), and 10% felsic rocks [Ramberg and Larsen, 1978]. The original lava volume and relative amount of RP lavas must, however, have been considerably larger. Volcanism in the Oslo Region started with extrusion of basalts (B_1) on a peneplain covered by up to 120-m-thick flood plain to braided stream deposits [Henningsmoen, 1978]. Extrusion of B_1 basalts was followed by eruptions of RP lavas (more than 30 flows) with occasional basalts, trachytes, and rhyolites. The Vestfold lavas have a present thickness of about 3000 m, of which about 1950 m are taken up by RP lavas [Ramberg and Larsen, 1978]. Near Skien (Figure 1) a 1500-m-thick sequence consisting of B_1 basalts only is preserved [Segalstad, 1979]. However, xenoliths of RP lavas preserved in the neighboring syenite [Oftedahl, 1952; Segalstad, 1979] indicate that the Skien basalts were also originally overlain by RP lavas. The 1600-m-thick lava pile at Krokskogen consists of about 1000 m of RP lavas (RP_1-RP_{17}), the rest basalts. The total thickness of lavas and the number of RP flows decrease northward to about 200 m [Ramberg and Larsen, 1978]. Major tectonic activity appears not to have occurred until well into the period of rhomb porphyry eruptions [Fjerdingstad, 1983; Larsen, 1978; Ramberg and Larsen, 1978]. It is therefore reasonable to assume that the thick isolated lava piles found in the rift today are the remnants of a continuous lava cover with decreasing thickness northward. This lava cover must have continued on to the flanks of the graben segments that comprise the Oslo Region. Evidence of this are large rhomb porphyry dikes in the Precambrian basement east and west of the Oslo Region. These dikes show that rhomb porphyry lava has ascended through the crust also outside the Oslo Graben. Further evidence comes from large volumes of rhomb porphyry conglomerates on a number of islands along the major fault along the east side of the Oslofjord (Figure 1). The transport direction is from the east and north, that is, from the eastern flank of the Vestfold Graben [Larsen et al., 1981; Størmer, 1935]. Oftedahl [1952] estimates the original RP lava volume to have been between 3500 and 13,500 km^3.

Results

Before we proceed to calculate excess masses, some calculations and assumptions on rock densities are needed.

Average cumulus mineral compositions for each crystallization stage (I, II, III, IV) expressed in terms of main end-members are listed in Table 3. On the basis of the densities of these data relevant at 25°C and a pressure of 1 bar, the cumulus assemblages I, II, III, and IV may be estimated. The necessary corrections for compressibility and thermal expansion at 4 kbar and 200°C (cf. gravity and thermal models above) were carried out; results are presented in Table 3. We assume a density of the intercumulus material (ρ_{RI}) equal to that of larvikite (2.71 g/cm^3). For ρ_P we use the mean density of the Precambrian crust unaffected by Permian rifting and volcanism, in the relevant depth range for the cumulate body, that is, 2.83 g/cm^3. The petrological modeling presented above implies that F=0.45, corresponding to stages I-III. The densities of the relevant cumulates may be calculated on the basis of (2), (3), and (4), which imply that

$$\rho_{CR} = (1-R)\rho_C + R\,\rho_{RI} \qquad (22)$$

Results are presented in Table 4. A higher value of ρ_{RI} than the value selected above implies a higher excess mass $\Delta M'_{Cr}$ (12), provided that masses of cumulus phases are constant.

Equations (12) and (21), and most of the data needed to estimate excess mass in the crust represented by cumulates and residues after anatexis, are presented above. However, two important parameters are not quantified because of insufficient information. One such parameter is the volume proportion (R) of trapped liquid in the cumulates. The other is the mass proportion of anatectic material (C) in the intrusions with a "mixed" or unknown origin (Table 3). The excess mass is therefore estimated and presented as a function of one or the other of these parameters (Figure 4).

We have chosen to calculate excess masses separately for (1) southern Vestfold Graben and (2) the Akershus Graben and central Oslo Region; we here find two large batholiths well exposed (and studied). There is, however, an important difference. In the southern Vestfold Graben, felsic rocks of mantle origin dominate, while in the other region the origin of felsic rocks is mainly mixed or "unknown" (Table 1, Figure 1).

Southern Vestfold Graben

The total mass of felsic rocks in the southern Vestfold Graben is estimated to be 3.75×10^{16} kg today (Table 1), of which 2.74×10^{16} kg represent larvikites and RP lavas believed to have a mantle origin. The remaining mass is made up by minor intrusive bodies with a mixed or unknown origin.

The excess mass of cumulates per meter along the graben axis corresponding to larvikites and

TABLE 3. Phase Assemblages and Average Mineral Compositions of Cumulus Phases at Different Stages of Crystallization (see Table 2 for Explanation) and Densities used in Cumulate Density Estimates

		Stage			
4 kbar, 200°C	Density g/cm^3	I	II	III	IV
Fraction of Melt		1.0-0.9	0.9-0.7	0.7-0.45	0.45 →
Olivine		(100)	(20)	(18)	(8)
Mg_2SiO_4	3.21	91	88	75	55
Fe_2SiO_4	4.39	9	12	25	45
Clinopyroxene			(80)	(77)	
$CaMgSi_2O_6$	3.28		67	59	
$CaFeSi_2O_6$					
$CaFeAlSiO_6$	3.64		17	26	
$NaFeSi_2O_6$					
$CaAl_2SiO_6$	3.40		16	15	
$NaAlSi_2O_6$					
Magnetite				(5)	(4)
Fe_3O_4	5.19			67	59
$TiFe_2O_4$	4.77			33	41
Plagioclase					(86)
$CaAl_2Si_2O_8$	2.76				20
$NaAlSi_3O_8$	2.61				60
$KAlSi_3O_8$	2.57				20
Apatite	3.18				(2)
Weighted density		3.32	3.36	3.50	2.83

Numbers in parantheses give percent of each mineral phase in each assemblage. The composition of the phases is given in terms of mole percent end-members. Densities [Deer et al., 1963; Johnson and Olhoeft, 1984; Robie et al., 1966] are adjusted to 4 kbar and 200°C (presumed states of cumulate) by using correction methods and data on compressibility and thermal expansion coefficients given by Birch [1966], Castellan [1971], Skinner [1966], and Sumino and Anderson [1984].

RP lavas observed today is calulated as a function of volume proportion of trapped liquid (R), using (12). The result is presented in Figure 4 as the curve a.

To include additional excess mass per meter corresponding to felsic rocks of mixed or unknown origin, we calculated both, assuming all rocks to have an anatectic origin (21) and a mantle origin (12). The results are presented in Figure 4 as the curves b and c, respecitvely. The total excess mass from felsic rocks used in our calculations must lie somewhere between curves b and c. The excess masses per meter represented by Wessel's [1984] mid crustal dense body, as estimated from his density profiles VIII to X, are shown for comparison.

Figure 4 reveals a striking agreement between the magnitudes of estimated excess masses in the crust under the southern Vestfold Graben using petrological and gravimetric methods, for low proportions of trapped liquid (R<0.20). This agreement lends strong support to the validity of the petrological method used to estimate the masses of cumulates and dense residues in the crust.

If we accept that both the geophysical and petrological mass estimates are realistic, the agreement between the results (data sets) is somewhat surprising. The geophysical results give an estimate of the total excess mass that actually exists in the crust. Now the petrological method, however, calculates the excess mass caused by cumulates and residues corresponding to felsic rocks exposed today; that is, felsic rocks removed by erosion are desregarded. However, all available geological observations imply that significant volumes of RP lavas (plus basalts, rhyolites, and ignimbrites) have been eroded away since Permian time. It should be noted that also rhyolites and ignimbrites observed today have been excluded in the calculations. Furthermore, most of the basaltic lavas have a history of fractional crystallization before extrusion [Neumann, et al., 1985; Øverli, 1985; Segalstad, 1979]. Also such cumulates have been disregarded. Curves b and c in Figure 4 thus represent very conservative values. We would consequently expect the petrological method to give lower excess mass estimates than the geophysical method. This is not the case. It may therefore be concluded on the basis of the data presented in Figure 4 that although it is probable that the excess mass in the dense midcrustal body defined by Wessel [1984] consists of dense Permian cumulates and residues after anatexis, such cumulates and residues also exist outside this midcrustal body. These surplus masses of cumulates and residues may be located in the lower crust (where normal densities are rather high) or alternatively, in the upper mantle, and may be calculated by using the difference

TABLE 4. Estimated Density of Oslo Region Cumulates and Residues After Anatexis Together with Data on Various Natural Rocks

Rock Types	Mean Density g/cm^3	Range of Densities g/cm^3	Reference
Oslo Region (200°C, 4kbar)			
Cumulates (R=0.06)	3.38		
Cumulates (R=0.40)	3.14		
Residues	2.89		
Published data (25°C, 1 bar)			
Dunite	3.277	3.214-3.314	Daly et al. [1966]
Dunite		2.98 -3.76	Johnson and Olhoeft [1984]
Pyroxenite	3.231	3.10 -3.318	Daly et al. [1966]
Gabbro	2.976	2.850-3.120	Daly et al. [1966]
Norite	2.984	2.720-3.020	Daly et al. [1966]
Diorite	2.839	2.721-2.960	Daly et al. [1966]
Quartz diorite	2.806	2.680-2.960	Daly et al. [1966]
Eclogite	3.392	3.338-3.452	Daly et al. [1966]
Peridotite	3.234	3.152-3.276	Daly et al. [1966]
Vestby layered gabbro, Oslo Region	3.204	2.73 -3.64	Ramberg [1976]
Wehrlite, Bushveld complex	3.369	3.356-3.380	Birch [1960]
Dunite xenoliths, Hawaii		3.01 -3.66	Jackson et al. [1981]
Wehrlite xenoliths, Hawaii		3.02 -3.37	Jackson et al. [1981]

The highest densities reported by Ramberg are due to "high contents of magnetite in some pyroxenites and gabbros"; the densest dunite reported by Jackson et al. contains 7% modal chromite. R is volume proportion of trapped liquid (see text for discussion). As index of fractional crystallization F, we have applied the value F=0.45 (see text).

between excess masses from petrological and gravimetric methods, respectively (provided that these methods are valid).

The Akershus Graben and Central Oslo Region

The Akershus Graben and central Oslo Region are dominated by intrusive rocks of mixed and unknown origin. As the mass proportion (C) of rocks with an anatectic origin in these intrusions is unknown, the excess mass of cumulates and dense residues is estimated as a function of C. In addition comes the excess mass caused by the cumulates corresponding to the RP lavas. The results are presented in Figure 4 together with excess masses estimated from Wessel's [1984] density profiles III to VII.

The Akershus Graben and central Oslo Region (Figure 4) also show very good agreement between excess mass estimates using petrological and gravimetric methods. If the Nordmarka-Hurdal and Finnemarka intrusive complexes have less than 40% ($C<0.4$) rocks formed from anatectic melts, the petrological present-day and the gravimetric models give similar values for excess mass per meter in the crust. Such a value for C is in agreement with the geochemical data, which show a wide range of compositional types in the Nordmarka-Hurdal intrusion, including mantle-derived units [Tuen, 1985]. A value for C below 0.4 therefore seems more likely than a high one.

Discussion and Conclusions

The major results obtained in the foregoing sections may be summarized as follows.

1. It is possible to estimate the hidden masses of cumulates and residues after partial melting on the basis of petrological/geological data.
2. The intracrustal surplus masses along the Oslo Region are caused by cumulates and residues after anatexis formed during the Permian rifting event.
3. From comparison of gravimetric and petrological results, we conclude that cumulates and dense residues also exist outside the dense midcrustal body defined on the basis of geophysical data, at least in the southern Vestfold Graben.

We will look closer at the consequence of these results with respect to the composition of different parts of the crust.

The cumulate density (22) decreases with increasing proportion of trapped liquid from 3.38 (R=0.06) to 3.14 g/cm^3 (R=0.40; Figure 4). These estimates lie within the range of published data on dunites and pyroxenites (Table 4) [Birch, 1960; Daly et al., 1966; Johnson and Olhoeft, 1984; Ramberg, 1976]. Wessel's [1984] midcrustal dense body ranges from 2.85 (~10-km depth) to 2.95-3.00 g/cm^3 (~22-km depth), with an average density of 2.89 g/cm^3. This means that the midcrustal dense body can nowhere consist of cumulates alone but must include a considerable proportion of rocks of lower density, for example, Precambrian rocks.

The density of residues after partial melting may be calculated from (19). Twenty percent melting of the Precambrian crust in southeastern Norway would (with the restrictions defined above) leave a residue with a density of about

2.89 g/cm^3, that is, similar to the average density of the midcrustal body. Considerable dehydration and mineral reactions during anatexis would, however, leave denser residues.

The mass proportion (a) of cumulates (M_{CR}) mixed with less dense rocks (M_L) in the midcrustal body (M_W) [Wessel and Husebye, 1986] may be estimated as follows:

$$M_{CR} = a\,M_W \text{ or } V_{CR}\,\rho_{CR} = a\,V_W\,\rho_W \tag{23}$$

$$M_L = (1-a)M_W \text{ or } V_L\rho_L = (1-a)V_W\rho_W \tag{24}$$

$$V_W = V_{CR} + V_L \tag{25}$$

These equations may be combined to give

$$a = \rho_{CR}(\rho_W - \rho_L)/\rho_W\,(\rho_{CR} - \rho_L) \tag{26}$$

If we assume that the midcrustal body consists exclusively of a mixture of cumulates and Precambrian rocks (average density at the level of the midcrustal body is 2.83 g/cm^3), the mass proportion of cumulates ranges from 0.13 (R=0.06) to 0.21 (R=0.40). The minor mass of residues expected in the crust under the southern Vestfold Graben will not significantly change these proportions. Under the Akershus Graben and central Oslo Region, however, the masses of residues and cumulates may be of similar magnitude. If we assume equal masses of residues and cumulates, the proportion of each will lie between about 0.1 and 0.2. This means that 60-87% of the midcrustal dense body consists of rocks other than ultramafic cumulates or residues after anatexis.

In addition to cumulates, residues after anatexis, and Precambrian rocks, the midcrustal body may comprise gabbroic rocks formed from mantle-derived basaltic melts that crystallized to completion in the crust. In the pressure range 2-6 kbar, gabbroic rocks are expected to have densities in the range 2.72-3.12 g/cm^3 [Table 3; Daly et al., 1966].

Is it correct to assume that both cumulates and residues after melting exist in the crust in the depth range 6-27 km? Studies on layered intrusions and cumulate-type xenoliths imply that such rocks may be found at any depth in the crust. In the Oslo Region, cumulate-type rocks are found in a series of gabbroic intrusions now exposed by erosion [e.g., Steinlein, 1981; Neumann et al., 1985], and as xenoliths in diabase dykes and a few basalt flows. Fluid inclusion studies of olivine-clinopyroxenite inclusions in a basalt at Krokskogen give minimum pressure estimates for the formation of the cumulates of 5 kbar (T. Andersen, personal communication, 1984). On this basis, there is no objection to the possibility of having cumulates in the dense midcrustal body.

Residues after anatexis present a larger problem. The solidus temperature of felsic rocks is 650°C or higher, depending on composition, water content, and pressure [e.g., Piwinskii, 1973; Steiner et al., 1975]. Anatexis will thus only occur below the 650°C isotherm. We do not know the geothermal gradient under the Oslo Region in Permo-Carboniferous time. However, the Rio Grande rift may present a present-day analogy to the Oslo rift during early Permian time. Heat flow measurements [Decker and Smithson, 1975] and P-T estimates based on crustal xenoliths [Padovani and Carter, 1977] independently imply a geothermal gradient that reaches 650° and 1200°C at about 18- and 38-km depths, respectively. In the active volcanic zone of southeastern Australia P-T estimates from crustal xenolith data suggest gradients with 900°C between 25- and 35-km depth [O'Reilly and Griffin, 1984]. In these areas, anatexis can only be expected in the lowermost part of the depth range of the midcrustal body under the Oslo Region. In order to obtain extensive anatexis up to depths of 6-9 km, a geothermal gradient similar to that determined for the active spreading zone of Iceland (650°C at about 5-km depth) [Oskarsson et al., 1982] is necessarry.

Regional geothermal conditions in the Oslo rift in Permian time similar to those in the active zone of Iceland seem unlikely. However, the intrusion of large volumes of mafic melts (at temperatures of 1200-1300°C) into the intermediate crust might cause anatexis in the side rock. Such a process would easily lead to mixing between mantle-derived and anatectic melts, as appear to be the case in the Oslo Region.

An important result of the excess mass estimates presented above is that dense cumulates apparently occur also outside the anomalous midcrustal body, at least in the southern Vestfold Graben. These cumulates may exist (1) in the crust below midcrustal body or (2) at the mantle-crust boundary. Available geophysical data neither support nor deny either possibility. Wessel and Husebye's [1986] data show no density contrast between the lower crust inside and outside the rift that can support possibility (1). Gundem [1984], however, suggests slightly higher P wave velocities and a less marked Moho contrast inside than outside the graben. Although uncertain, these data favor the possibility of cumulates in the lower crust. Finally, it should be noted that the estimated cumulate densities fall within the range of values typical of upper mantle rock types, that is, peridotite and eclogite (Table 4).

The Moho depth is 32-35 km inside and 35-38 km outside the graben [Bertheussen, 1977]; this is linked with a moderate crustal stretching and thinning [Ramberg, 1976; Wessel and Husebye, 1985]. Some material below this moderate Moho upwarp is likely to be cumulates. Cumulates or dense residues after anatexis may also account for the more transitional nature of Moho inside the graben.

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References

Andersen, T., Crystallization history of a Permian composite monzonite - alkali syenite pluton in the Sande cauldron, Oslo rift, southern Norway, Lithos, 17, 153-170, 1984.

Andresen, P. A., Geochemical investigation aimed at a chemical - stratigraphic identification of the lower rhomb porphyry lavas in the central Oslo Graben (in Norwegian), Candidatus Scientiarum thesis, 109 pp., Univ. i Oslo, Norway, 1985.

Barth, T. F. W., Studies on the igneous rock complex of the Oslo Region, XIV, Provenance of the Oslo magmas, Skr. Norske Vidensk. Akad. Oslo I, Mat. Naturv. Kl. 1954, no. 4, 1-20, 1954.

Basalt Volcanism Study Project, Basaltic Volcanism on the Terrestrial Planets, 1286 pp. Pergamon, New York, 1981.

Bertheussen, K.-A., Moho depth determinations based on spectral ratio analysis at NORSAR, Phys. Earth Planet. Inter., 15, 13-27, 1977.

Birch, F., The velocity of compressional waves in rocks to 10 kilobars, 1, J. Geophys. Res., 65, 1083-1102, 1960.

Birch, F., The velocity of compressional waves in rocks to 10 kilobars, 2, J. Geophys. Res., 66, 2199-2224, 1961.

Birch, F., Compressibility; elastic constants, Handbook of Physical Constants, Geol. Soc. Am. Mem., 97, 98-173.

Castellan, G. W., Physical Chemistry, Addison-Wesley, Reading, Mass., 1971.

Cox, K. G., and J. D. Bell, A crystal fractionation model for basaltic rocks of the New Georgia Group, British Solomon Islands, Contrib. Mineral. Petrol., 37, 1-13, 1972.

Cox, K. G., J. D. Bell, and R. J. Pankhurst, The Interpretation of Igneous Rocks, 450 pp., George Allen and Unwin, London, 1979.

Daly, R. A., G. E. Manger, and S. P. Clark, Density of rocks, Handbook of Physical Constants, Geol. Soc. Am. Mem., 97, 20-26, 1966.

Decker, E. R., and S. B. Smithson, Heat flow and gravity interpretation across the Rio Grande Rift in southern New Mexico and west Texas, J. Geophys. Res., 80, 2542-2552, 1975.

Deer, W. A., R. A. Howie, and J. Zussman, Rock Forming Minerals, 2, 379 pp., Longmans, London, 1963.

Fjerdingstad, V., Geochemistry and petrology of magmatic rocks in the Nittedal Cauldron, Oslo Graben (in Norwegian), Candidatus Scientiarum thesis, 129 pp., Univ. of Oslo, Norway, 1983.

Gundem, M. B., 2-D seismic synthesis of the Oslo Graben, Candidatus Scientiarum thesis, 164 pp., Univ. of Oslo, Norway, 1984.

Haenel, R., G. Grønlie, and K. S. Heier, Terrestrial heat flow determinations in Norway and an attempted interpretation, in Terrestrial Heat Flow in Europe, edited by V. Chermâk and L. Rybach, pp. 232-239, Springer-Verlag, New York, 1979.

Henningsmoen, G., Sedimentary rocks associated with the Oslo Region lavas, The Oslo Paleorift: A Review and Guide to Excursions, Norges Geol. Unders., 337, 17-24, 1978.

Jackson, E. D., D. A. Clague, E. Engleman, W. B. Friesen, and D. Norton, Xenoliths in the alkalic basalt flows from Hualalai volcano, Hawaii, U. S. Geol. Surv. Open File Rep., 81-1031, 1981.

Johnson, G. R., and G. R. Olhoeft, Density of rocks and minerals, in Handbook of Physical Properties of Rocks, vol. 3, edited by R. S. Carmichael, pp. 1-38, CRC Press, Boca Raton, 1984.

Larsen, B. T., Krokskogen lava area, The Oslo Paleorift: A Review and Guide to Excursions Norges Geol. Unders., 337, 143-162, 1978.

Larsen, B. T., P. A. Midtkandal, R. Steel, and O. Steinlein, Geology and tectonics of the central Oslofjord, Oslo Rift, in Excursion Guide to the 4th International Conference on Basement Tectonics, edited by B. T. Larsen, pp. 51-79, Univ. of Oslo, Norway, 1981.

Neumann, E.-R., Petrology of the plutonic rocks, The Oslo Paleorift: A Review and Guide to Excursions, Norges Geol. Unders., 337, 25-34, 1978.

Neumann, E.-R., Petrogenesis of the Oslo Region larvikites and associated rocks, J. Petrol., 21, 498-531, 1980.

Neumann, E.-R., B. T. Larsen, and B. Sundvoll, Compositional variations among gabbroic intrusions in the Oslo Rift, Lithos, 18, 35-59, 1985.

Oftedahl, C., Studies on the igneous rock complex of the Oslo Region, XII, The lavas, Skr. Norske Vidensk. Akad. Oslo I, Mat. Naturv. Kl. 1952, no. 3, 64 pp., 1952.

Oftedahl, C., Permian rocks and structures of the Oslo Region, Geology of Norway, Norges Geol. Unders., 208, 298-343, 1960.

Oftedahl, C., Magmen-Entstehung nach Lava-Stratigraphie in Südlichen Oslo-Gebiete, Geol. Rundsch., 57, 203-218, 1967.

O'Reilly, S. Y., and W. L. Griffin, A xenolith-derived geotherm for southeastern Australia and its geophysical implications, Tectonophysics, 111, 41-63, 1984.

Oskarsson, N., G. E. Sigvaldason, and S. Steinthorsson, A dynamic model for rift zone petrogenesis and the regional petrology of Iceland, J. Petrol., 23, 28-74, 1982.

Øverli, P. E., Stratigraphy and petrology of the Horten basalts (B_1 niveau), southern Oslo Graben (in Norwegian), Candidatus Scientiarum thesis, 106 pp., Univ. of Oslo, Norway, 1985.

Padovani, E. R., and J. L. Carter, Aspects of the deep crustal evolution beneath south central New Mexico, in The Earth's Crust, Geophys. Monogr. 20, edited by J. G. Heacock, pp. 19-55, AGU, Washington, D. C., 1977.

Piwinskii, A. J., Experimental studies of igneous rock series, central Sierra Nevada batholith, California, II, Neues Jahrb. Mineral. Abh., 1973, 193-215, 1973.

Presnall, D. C., S. A. Dixon, J. R. Dixon, T. H. O'Donnell, N. L. Brenner, R. L. Schrock, and D. W. Dycus, Liquidus phase relations on the join diopside-forsterite-anorthite from 1 atm to 20 kbar: Their bearing on the generation and crystallization of basaltic magma, Contrib. Mineral. Petrol., 66, 203-220, 1978.

Ramberg, I. B., Gravity interpretation of the Oslo Graben and associated rocks, Norges Geol. Unders., 325, 194 pp., 1976.

Ramberg, I. B., and B. T. Larsen, Tectonomagmatic evolution, The Oslo Paleorift: A Review and Guide to Excursions, Norges Geol. Unders., 337, 55-73, 1978.

Rasmussen, E., A petrological and geochemical investigation of Permian supracrustal and intrusive rocks north of Øyangen, northern Oslo Region (in Norwegian), Candidatus Realium thesis, 169 pp., Univ. of Oslo, Norway, 1983.

Robie, R. A., P. M. Bethke, M. S. Toulmin, and J. L. Edwards, X-ray crystallographic data, densities, and molar volumes of minerals, Handbook of Physical Constants, Geol. Soc. Am. Mem., 97, 27-74, 1966.

Segalstad, T. V., Petrology of the Skien basaltic rocks, southwestern Oslo Region, Norway, Lithos, 12, 221-239, 1979.

Skinner, B. J., Thermal expansion, Handbook of Physical Constants, Geol. Soc. Am. Mem., 97, 75-96, 1966.

Steiner, J. C., R. H. Jahns, and W. C. Luth, Crystallization of alkali feldspar and quartz in the haplogranite system $NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2- H_2O at 4 kb, Geol. Soc. Am. Bull., 86, 83-98, 1975.

Steinlein, O., Petrology and geochemistry of layered gabbroic volcanic necks at Hurum, Oslo Graben (in Norwegian), Candidatus Realium thesis, 93 pp., Univ. of Oslo, Norway, 1981.

Størmer, L., Contribution to the geology of the southern part of the Oslofjord: The rhomb-porphyry conglomerate with remarks on younger tectonics, Norsk Geol. Tidsskr., 15, 43-113, 1935.

Sumino, Y., and O. L. Anderson, Elastic constants of minerals, in Handbook of Physical Properties of Rocks, vol. 3, edited by R. S. Carmichael, pp. 39-138, CRC Press, Bocca Raton, Fla., 1984.

Sundvoll, B., Rb/Sr-relationship in the Oslo igneous rocks, in Petrology and Geochemistry of Continental Rifts, edited by E.-R. Neumann and I. B. Ramberg, pp. 181-184, D. Reidel, Hingham, Mass., 1978.

Tryti, J., and M. A. Sellevoll, Report on a reconnaissance seismic crustal study of the Oslo Rift, in The Norwegian Geotraverse Project, edited by K. S. Heier, pp. 151-183, Norges Geol. Unders., Trondheim, 1977.

Tuen, E., A geochemical study of acid intrusive rocks at Nordliskampen, Hurdal (in Norwegian), Candidata Scientiarum thesis, 108 pp., Univ. of Oslo, Norway, 1985.

Wessel, P., Gravity inversion and Oslo Graben taphrogenesis, Candidatus Scientiarum thesis, 123 pp., Univ. of Oslo, Norway, 1984.

Wessel, P., and E. S. Husebye, The Oslo Graben gravity high and taphrogenesis, Tectonophysics, in press, 1986.

Wyllie, P. J., Crustal anatexis: An experimental review, Tectonophysics, 43, 41-71, 1977.

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