Geophysical Investigations*

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Introduction

The formation of the Oslo Rift represents a major event in the geological history of Scandinavia. Its creation started and also culminated during Permo–Carboniferous times, while the underlying dynamic processes probably ended before the Tertiary. The life span of the Oslo Rift in terms of volcanism and lateral and vertical movements might be read from the geology of the area. Although the geological data are most valuable in deciphering the deformation of the uppermost layers of the Oslo Rift and in particular the Oslo Graben, this kind of information is not fully adequate for a proper understanding of the associated deep-seated geodynamic processes. In this respect, geophysical methods are important as such investigations in principle are capable of detecting and localizing anomalous structures in the lithosphere in sufficient detail for improving our understanding of the dynamic development of the area in question.

In this synopsis of the geophysics of the Oslo Rift, we will present the essentials of various types of geophysical investigations undertaken in the Oslo Rift area proper. The emphasis will be on gravity surveys, which provide a detailed picture of the magmatic intrusions into the crustal part of the graben, while inversion of seismological data from the large array NORSAR, overlying the northern end of the Oslo Graben (see Fig. 1), provides exceptionally detailed local mapping of the deeper part of the lithosphere. Before forwarding our review of the geophysical investigations in the Oslo Rift and adjacent areas, a brief outline of the tectonic setting of the region will be presented.

Tectonic setting of the Oslo Rift

The Oslo Graben which represents the central segment of the postulated Oslo Rift has subsided into the Precambrian gneisses of the Fennoscandian Shield (for details see Plate 1). Towards the north, the rift is associated with a series of generally N–S-trending faults. Towards the south an overall SW-trending submarine extension of the rift below the Skagerrak Sea has been hypothesized on the basis of both geological and geophysical observations, e.g. Ramberg 1972b, 1976, Ramberg & Smithson 1975a). The intersection between the Oslo

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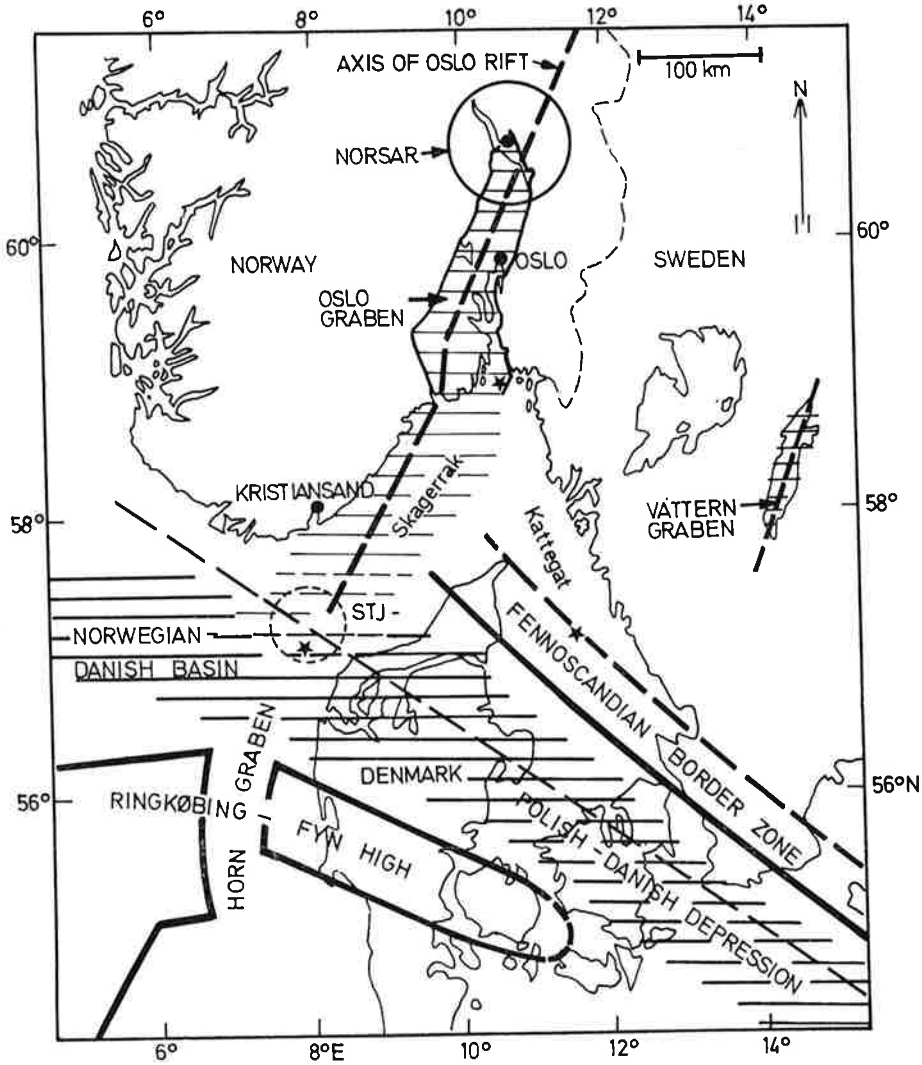


Fig. 1. Tectonic setting of the general Oslo Graben – Oslo Rift area. The diameter of the NORSAR array is indicated by a circle, while the presumed locations of the 3 largest recorded earthquakes are marked by stars. STJ – presumed location of the Skagerrak triple junction (the Jutland junction of Burke & Dewey (1973).

Rift and the Danish–Polish Depression represents a possible triple junction (Ramberg 1972b, Burke & Dewey 1973, Whiteman et al. 1975). Thus the Oslo Rift, which appears to be part of a regional fracture system in northwestern Europe, may essentially be interpreted as a Permo-Carboniferous 'failed arm'. The rather voluminous axial intrusive, however, testify that the crustal break-up was accompanied by lateral spreading, especially in the southern parts of the graben. For a general discussion of lithospheric instabilities, we refer to a paper by Bridwell (1976).

The central segment, the Oslo Graben, is an area of intense faulting and flexuring, volcanism and igneous intrusion. Accumulated vertical displacements along normal faults are of the order of 1 km, and occasionally exceed 3 km in some parts of the graben. Furthermore, the Oslo Graben is subdivided by minor faults into a system of small-scale tilt-blocks, horsts and grabens. In addition to these linear features, we also find pronounced systems of ring complexes and cauldrons, the appearance and average diameter (about 12 km) of which imply an origin from initially rising magma masses from intermediate crustal depths. Parts of the ring-shaped and linear fault systems of the graben were subsequently obliterated by emplacement of large felsitic to intermediate batholiths which in turn rose to the surface chiefly by the process of magmatic stoping.

Geophysical surveys in the Oslo Rift zone

It is deemed proper to start with gravity because this was the first method to be utilized in geophysical exploration of the Oslo Rift area; moreover, the observed gravity anomalies exhibit good correlation with the surface geology of the graben. We will then discuss magnetic and seismic surveys, heat flow measurements and also data bearing on the rate of crustal uplift. Finally, observational data on the earthquake activity in the Oslo Rift will be presented.

GRAVITY SURVEYS

A Bouguer gravity map of the Oslo region was published in 1960 by the Norwegian Geographic Survey (NGO), Oslo. From that map it was apparent that the graben is associated with a strong, positive gravity anomaly, a feature which in turn encouraged detailed gravity investigations of the whole area (Smithson 1961, Ramberg 1972b, 1976). The Oslo gravity high can easily be traced southwestwards into the Skagerrak Sea (Sorgenfrei 1969, Ramberg & Smithson 1975a), where it gradually decreases in intensity due to the blanketing effect of the less dense but thick sedimentary deposits in these southern areas (Fig. 2). Similarly, negative gravity anomalies occur over the central part of the deep, sediment-filled, NW–SE-trending Danish–Polish Depression, whereas the flanking Fennoscandian Border Zone is roughly followed by a ca. 30 mgal gravity high. The largest gravity high occurs outside Kristiansand and has been interpreted by Åm (1973) as a composite high-density volcanic plug of possible Permian and/or Tertiary age. It is situated close to the intersection between the Oslo Rift and the Danish–Polish Depression, or the postulated Skagerrak (or Jutland) triple junction, shown in Fig. 1.

Comprehensive analyses of the Oslo Graben gravity data have recently been presented by Ramberg (1972a, 1976) with emphasis on the geotectonic implications. More than 1900 density measurements have been made on samples from the graben area and adjacent Precambrian rocks. The weighted mean density of the Permian plutonic rocks is about 2.66 g/cm^3, which contrasts with a value for the denser Precambrian gneisses of 2.74 g/cm^3.

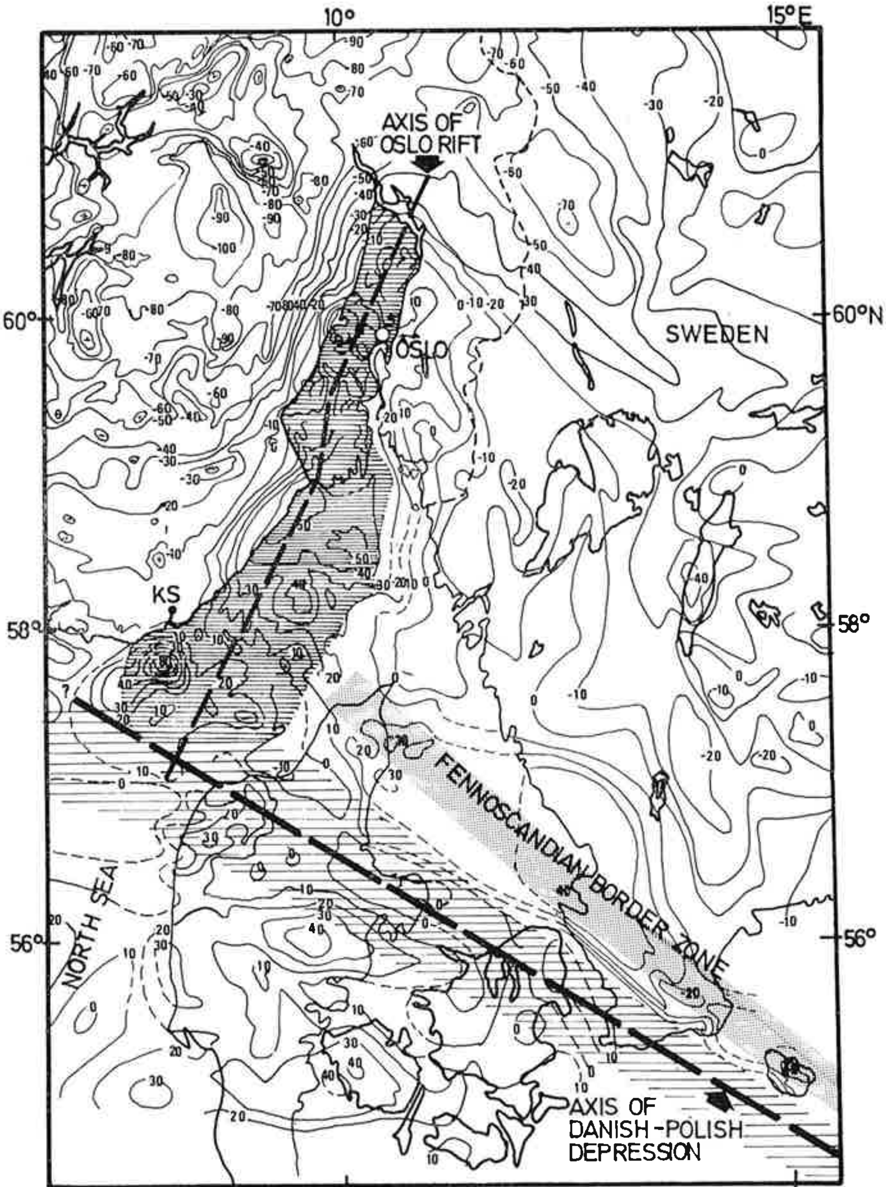


Fig. 2. Simplified Bouguer anomaly map over southern Norway and the adjacent Skagerrak and Kattegat Seas. KS – Kristiansand. (Figure redrawn from Ramberg 1971, 1976).

The detailed Bouguer gravity map (Plate 3) clearly reveals the distinct NNE-trending gravity high associated with the graben. Evidently the high is not causally connected with surface geology, particularly as it continues beyond the boundaries of the exposed graben along its axial directions (Fig. 2). Superimposed on this *regional* trend are many *local* anomalies which correlate closely with various felsic batholiths, cauldrons and other shallow features. Gravity

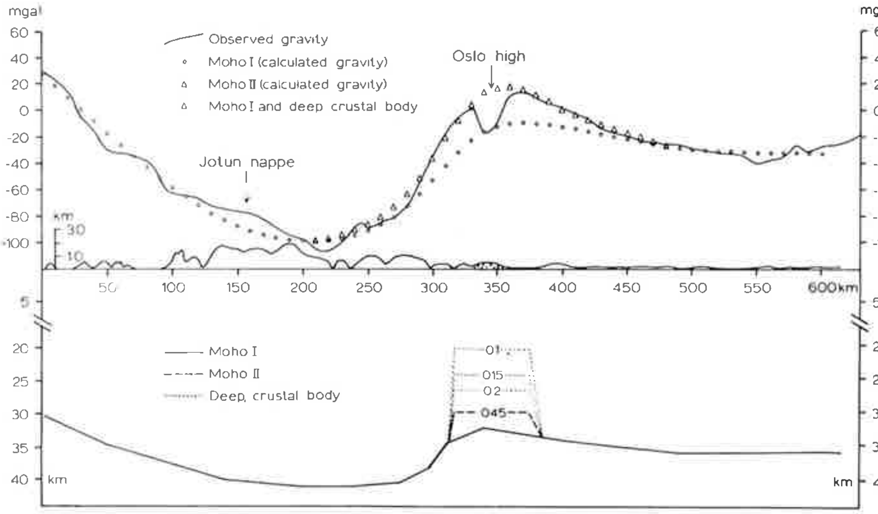


Fig. 3. Gravity profile across the northern part of the graben; the profile strikes WNW and is located approximately 30 km to the south of the NORSAR array centre shown in Fig. 1. Alternative crustal models explaining the observed broad gravity high are also shown. The corresponding density contrasts are indicated in the lower part of the figure. In particular, note the superimposed gravity low in the central parts of the profile, due to upper crustal felsic intrusions. (Figure redrawn from Ramberg 1976).

modelling implies that the larger batholiths extend to depths of 10–12 km, under the assumption of uniform density contrasts. However, xenoliths of denser rocks from the size of a few millimetres up to several kilometres occur throughout the batholithic complexes. Accordingly, it is reasonable to assume that because of the temperature distribution within the plutons (lower temperatures towards the walls) and because of viscous drag near these walls, the stoped blocks will tend the concentrate along the flanks and towards the bottom of the ascending bodies. If this implied density stratification model is valid, it follows that the felsic batholiths are both deeper and wider than inferred from the uniform density assumption.

Removal of all local gravity anomalies from the Bouguer anomaly map (Plate 3) leaves us with a dominant regional high that clearly demonstrates that the relatively low density felsic intrusives of the upper crust must have a counterpart of significant amounts of dense rocks at greater depths. Analysis suggests that the graben gravity high may be the combined effect of crustal thinning along the rift axis, and of a dense block of mafic rocks located in the lower part of the crust somewhere below the 'bottom' of the outcropping felsic batholiths. Gravity gradient analysis indicates that the upper level of the mafic body is localized on average about 20 km below the surface (reflecting an assumed density contrast of 0.1 g/cm^3).

Fig. 3, which is typical for gravity profiles across the northern part of the graben, illustrates various interpretations of the combined Moho upwarp and dense intrusive body. A smaller density contrast of the latter with respect to

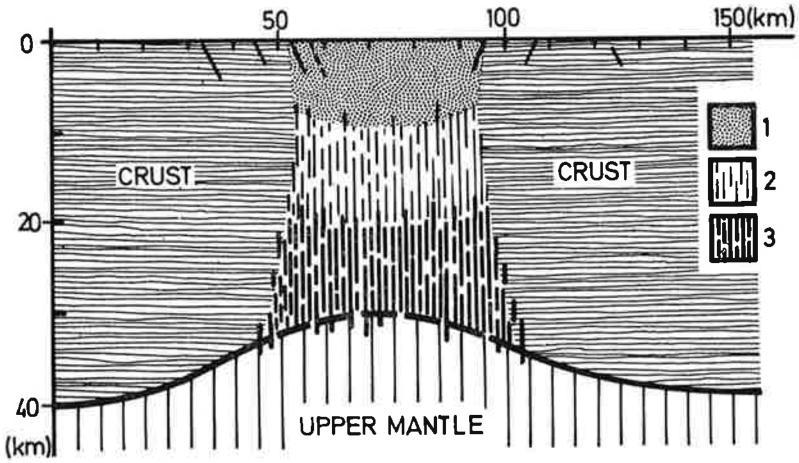


Fig. 4. Schematic section across the Oslo Graben with a hypothetical relatively thin crust which in turn has been subdivided in 3 principal parts: 1) an upper zone of largely intermediate to felsic intrusive rocks, 2) an intermediate zone of mixed rocks such as Precambrian gneisses and intrusive rocks of various composition, and 3) a lower zone of largely mafic to ultramafic rocks. (Figure redrawn from Ramberg 1976).

to ambient rocks would bring the anomalous body even higher up in the crust, a possibility which is in fact supported by gravity minimum depth calculations based on Parker's (1975) 'ideal body' concept (Husebye, England & Ramberg, in prep.).

The analysis of the gravity data also provides supporting evidence of an associated large-scale Moho upwarp (See Fig. 3). This feature has primarily been tied to the localization of the rift, but may, in part, also reflect crustal thickening associated with the Caledonides.

Mass calculations reveal a striking preponderance of dense (mafic to ultramafic) rocks over the felsic rocks by a ratio of about 10 : 1. This result combined with other geophysical and geological data suggests that the upper crustal felsic rocks of the graben possibly formed by fractional crystallization of a parental basaltic magma ultimately of asthenospheric origin. The deep-seated dense masses are located below the axis of the graben and have tentatively been interpreted as a paleorift asthenolith, formed as a result of fractional melting and buoyancy of mantle material. A simplified interpretational section across the Oslo Graben is presented in Fig. 4.

MAGNETIC SURVEYS

General aeromagnetic mapping of the Oslo Graben and its presumed extension into the Skagerrak has been carried out by the Geological Survey of Norway (NGU), Trondheim. Total intensity magnetic maps for these two areas are reproduced in Figs. 5 and 6. Only the Skagerrak data, sampled at an altitude of 3400 m, have as yet been interpreted, and in this respect we refer to Åm (1973) and Sellevoll and Aalstad (1971).

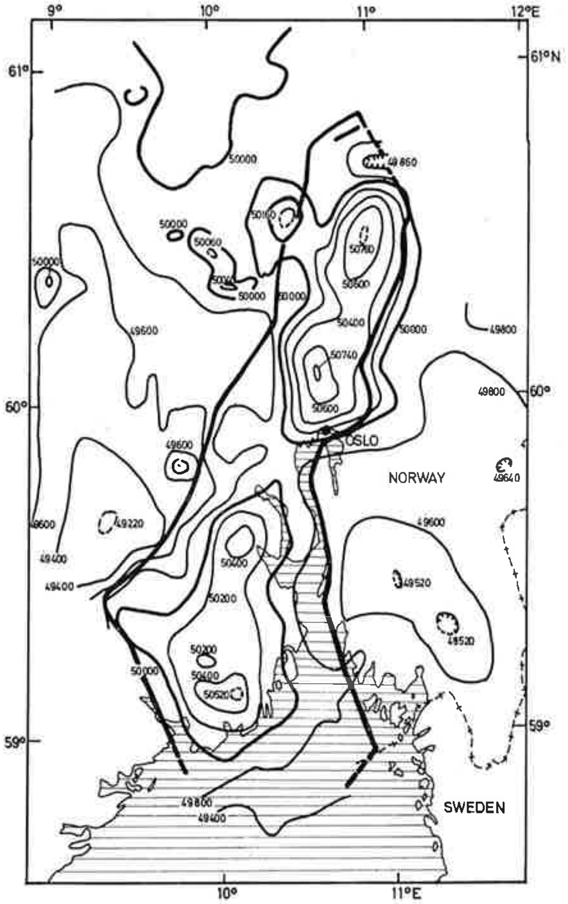


Fig. 5. Total magnetic intensity map with 200 gamma contour interval over the Oslo Graben (which is contoured by thick lines). Redrawn from an original NGU-map kindly made available by Dr. I. Aalstad, NGU. Flight altitude was 3350 m.

Marked magnetic anomalies are associated with the outcropping batholiths, the felsic to intermediate rocks of which exhibit a higher average magnetic susceptibility than the surrounding Precambrian gneisses. This was already clear from the regional survey of Hannaford and Haines (1969), which was flown at 10 000 feet, giving anomalies of 600 to 800 γ above the northern syenite complex (Nordmarka–Hurdalen) and the southern monzonitic complex (Skien–Skrim). Another magnetic anomaly of similar appearance occurs along the same axial trend in the Skagerrak at about 57°40′N, 8°40′E (see Fig. 6), and thus may outline another 'Oslo-batholith' at this locality. A sharp local magnetic anomaly further northwest outside Kristiansand (but not shown on Fig. 6) coincides with a marked gravity high and may possibly represent a high density volcanic plug as suggested by Åm (1973).

Whereas mass and shape of the various plutonic complexes have been inferred by means of the gravity studies, the magnetic measurements can only confirm the generally great vertical extents of the major batholiths, which are of the order of 10 km. Due to the increased sensitivity of the magnetic field for near-surface features, relevant data here clearly indicate outward-sloping

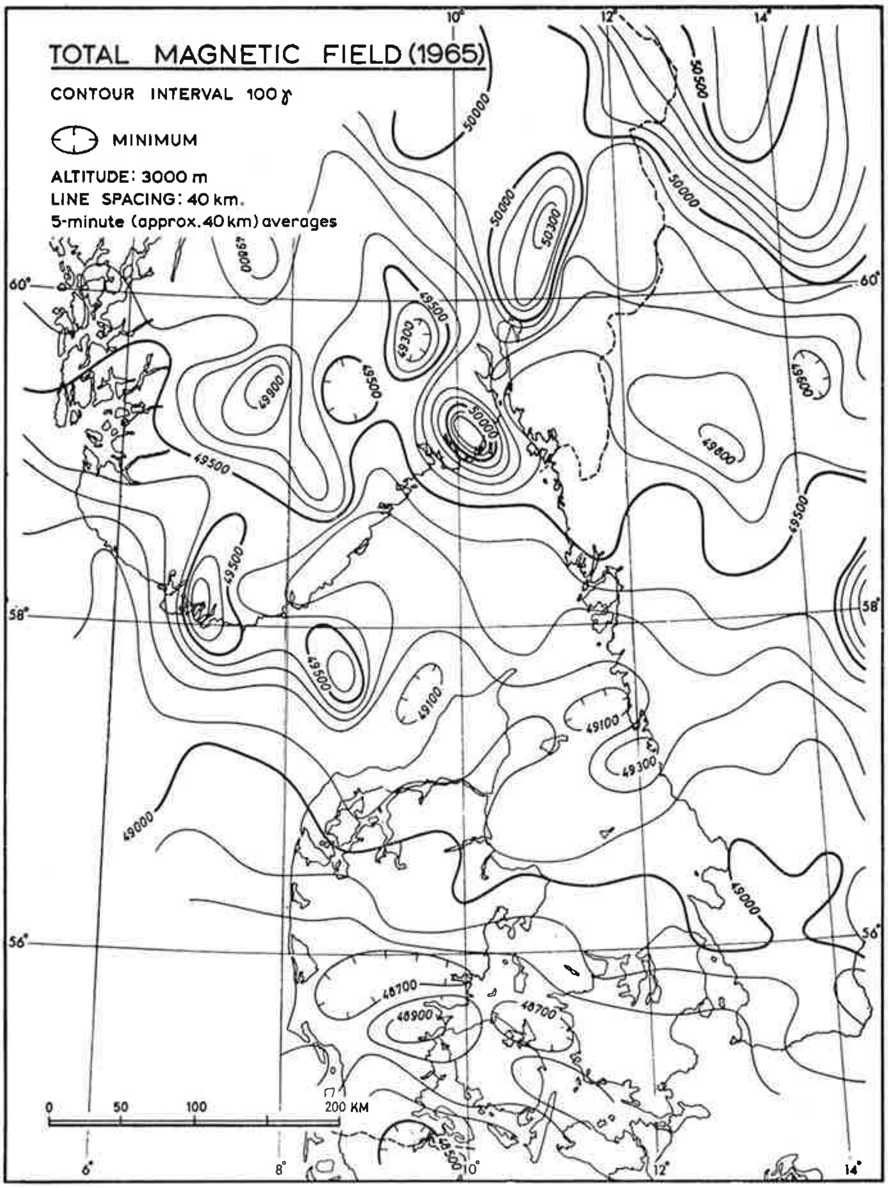


Fig. 6. Total magnetic intensity map for the Skagerrak and adjacent land areas (after Åm 1973). The Geological Survey of Norway (NGU) has also constructed a magnetic map (scale 1:250 000) for the Skagerrak area, based on a flight altitude of 150 m (Dr. I. Aalstad, personal communication, 1976).

contacts for many of the plutons, especially in the eastern and southern parts of the Oslo Graben. This supports the gravimetric results and shows that igneous provinces in genaral widen with depth. Furthermore, pronounced circular patterns on the NGU aeromagnetic maps outline a number of cauldrons and plutonic ring complexes. Also, within the larger composite batholiths, segments of concentric magnetic patterns are clearly discernible (Kristoffersen 1973, Petersen 1977).

SEISMOLOGICAL INVESTIGATIONS

The large aperture seismic array NORSAR is overlying the northern part of the Oslo Graben, as shown in Fig. 1. Up to October 1976 this array comprised 132 short-period seismometers and 22 three-component long-period seismometers which were organized in 22 subarrays (for details see Bungum et al. 1971). The high-quality digital recordings from NORSAR have been used rather extensively in seismic structural research, i. e., two- and three-dimensional seismic mapping of the lithosphere beneath the array. In this respect several approaches have been adopted as from the beginning it was quite obvious that the observed travel time and amplitude anomalies could not be explained in terms of conventional layer-models of the crust and upper mantle with uniform material properties. The first concentrated attempt to explain the NORSAR time and amplitude anomalies was in the context of acoustical wave propagation in random media. The essence of this concept was to obtain a measure of the extent of heterogeneities in the array siting area in terms of rms-velocity anomalies which amounted to around 3% (Berteussen et al. 1975). Although this approach could satisfactorily explain the observed time and amplitude anomalies, a drawback from a geotectonic point of view is that the existing inhomogeneities are described in statistical terms; in addition, the depth resolution is relatively poor.

The next attempt, which has proved to be very successful in the analysis of seismic data from widely different parts of the world, was a direct inversion of the two-dimensional travel time data, thus obtaining a three-dimensional image of the lithosphere beneath the NORSAR array and also, consequently, beneath the northern part of the Oslo Graben (for details, see Aki et al. 1977). Some of these results are presented in Figs. 7 and 8, which show the estimated seismic velocity anomalies for the bottom crustal layer and another layer at a depth of 126 km. Aki and co-workers tentatively assumed a lithospheric thickness of 126 km, an assumption which is not critical for their seismic inversion results. From Fig. 7 it is obvious that the graben contours do not have a too clear counterpart in the obtained seismic velocity pattern, and there are several possible reasons for this. A plausible explanation here is that the extent of velocity anomalies outside the graben is of the same order as those within. Another explanation might be that the graben is not sampled well enough by the array, and in addition the typical graben structures are less well-developed in its northern part as evidenced both by geological and by gravity observations. We remark in passing that experiments are now under way for a more detailed study of this problem by utilizing seismic waves which have travelled for a considerable distance within the presumed dense lower portion of the Oslo Graben area.

Another approach to detailed seismic structural research in the NORSAR siting area is that of Berteussen (1977) who has used the spectral ratio

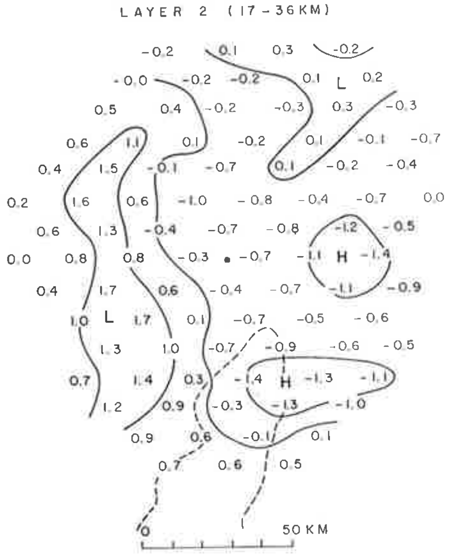


Fig. 7. Stochastic inverse solution for layer 2 (plan view – lower crust) in Aki and co-workers' (1977) lithospheric block model based on NORSAR array seismic travel time residuals. The numbers show the fractional seismic velocity perturbation in percent of the presumed average velocity of 6.9 km/sec. The letters L and H mark areas of low and high velocity anomalies, respectively, Alternatively, the L and H areas may correspond to a relative thickening and thinning of the crust. The array centre is marked by a dot while the Oslo Graben eruptives are indicated by dashed lines. (Figure redrawn from Aki et al. 1977.)

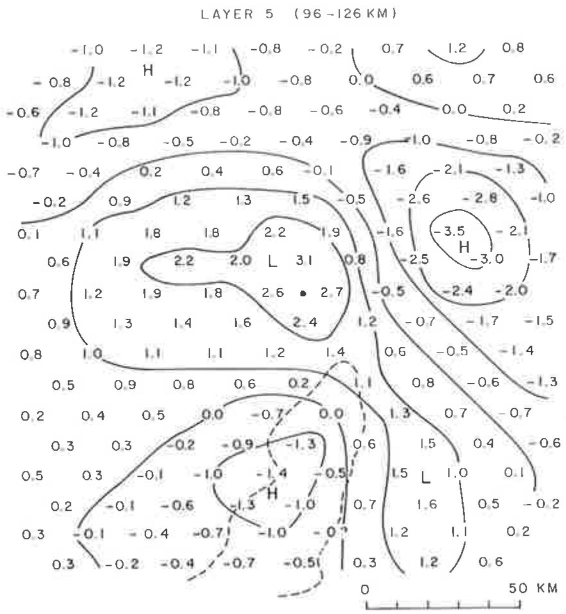


Fig. 8. Stochastic inverse solution for layer 5 (lower lithosphere – presumed depth range 96–126 km) in Aki and co-workers' (1977) lithospheric block model. Average layer velocity is 8.2 km/sec. See Fig. 7 for explanation of symbols. (Figure redrawn from Aki et al. 1977.)

technique for estimating crustal thickness beneath the various subarrays (see Fig. 9). These results are in good agreement with those of Aki et al. (1977) presented in Fig. 7. Berteussen's findings indicate that crustal thickness increases westward, a conclusion which is in harmony with the other cited results of relatively low velocities towards the west. Both the quoted seismic results are apparently also in good harmony with Ramberg's gravity interpretatons (see Fig. 3), although the smaller sampling area represented by the

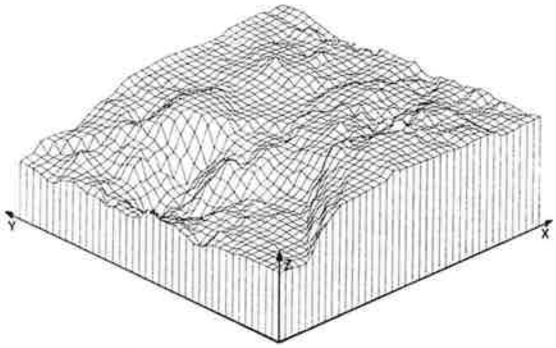


Fig. 9. Moho depth contours estimated from spectral-ratio analysis of long-period P-wave recordings from the 22 NORSAR subarrays. The y-axis points westwards and the x-axis northwards. The array centre is in the middle of the figure, that is, 50 km from the respective axes indicated in the figure. The estimated crustal thicknesses range from 32 km (in the east) to 38 km (in the southwestern part). (Figure after Berteussen 1977.)

NORSAR (situated partly to the north of the graben), is not anticipated to resolve Moho undulations of low gradients (<5°) and wavelengths of the order of hundred of kilometers. In Ramberg's (1976) interpretation, Fig. 3 only represents a preliminary model of uniform lateral density contrast. A second intepretational step taking into consideration the light granitoid composition of the Precambrian crust to the east of the graben, leads to Moho upwarp symmetrically arranged with respect to the graben axis (Ramberg 1976, fig. 74a). In this respect, seismic surveys are deemed inconclusive in view of the scatter in the final results. For example, the estimated crustal thicknesses may differ by as much as 4 to 8 km within small areas and, in addition, crustal layering appears problematic as 2, 3 and even 4 layers have been proposed.

NORSAR data have also been used extensively for research on large-scale structures beneath Fennoscandia and adjacent areas and here it suffices to refer to recent work by England and coworkers (1977), Haddon and Husebye (in prep.) and Ringdal and Husebye (1977). Also, various refraction and wide-angle reflection surveys have been undertaken in the general Oslo Rift Zone (e.g., Weigel et al. 1970, Dahlman 1971, Sellevoll 1972, Massé 1975, Tryti & Sellevoll 1977, Kanestrøm 1977). The latter investigations have provided some information on structural features such as crustal layering and thicknesses for the general area in question.

HEAT FLOW MEASUREMENTS

In recent years a relatively large number of heat flow measurements have been undertaken in Norway, and the majority of these observations are based on the new measurement technique of heat flow sampling from sediments in suitable lakes (e.g., Swanberg et al. 1974, Grønlie et al. 1977). From the 66 observations so far available, the average is very close to 1.0 hfu with a standard deviation of ± 0.23. Neither for Norway in general nor for the Oslo Graben in particular do the heat flow data exhibit any pronounced correlation with dominant lithological or tectonic units. With regard to the Oslo Graben, this implies that this area must be considered thermally inactive.

OTHER TYPES OF GEOPHYSICAL SURVEY

The glacial rebound in Fennoscandia is a well-known geophysical phenomenon (O'Connell 1976), in particular as in extreme cases like the northeastern coastal areas of Sweden the rate of uplift amounts to around 1 cm/year. In this respect we cannot exclude the possibility that part of the uplift is of tectonic origin, as indeed is the case for the presumed post-glacial Pärve fault in Swedish Lappland (Lundquist & Lagerbäck 1976). In the Oslofjord area mean water-level markers, some of which date back to 1839, and precise benchmark levelling surveys during the years 1927–32 and 1962–65, independently give an uplift rate of around 0.3 cm/year (Midtsundstad & Bakkelid 1977). In this respect the Oslo Graben does not exhibit particularly anomalous features and, besides, the wavelength of uplift rate changes exceeds the linear dimensions of the graben.

Paleomagnetic sampling of different types of intrusive and lavas in the Oslo Graben and Rift Zone has also been conducted; here we refer to the works of van Everdingen (1960), Storetvedt & Løvlie (1977) and Bylund & Patchett (1977).

Earthquake activity in the Oslo Graben and Oslo Rift zone

In general, seismic activity in Fennoscandia is modest and is considered typical of intraplate earthquake occurrence. The historical observations date back to around the year 1500 and indicate that earthquakes are most frequent in the western and northern coastal areas of Norway. Sometimes the observed seismicity exhibits a certain correlation with dominant tectonic features, as discussed by Husebye et al. (1977). With regard to the Oslo Graben, the seismic activity is relatively modest but on the other hand some of the very largest earthquakes experienced in Fennoscandia (magnitudes of the order 5.5–6.5 units) appear to be associated with the Oslo Rift and the branching Fennoscandian Border Zone. Specific references here are to the Kattegat Sea earthquake of 1759, the Skagerrak earthquake (presumably west of Limfjord, Jutland) of 1841, and the large outer Oslofjord earthquake of 1904. A peculiar feature of the Oslofjord event was an apparent surge in earthquake occurrence in the following 10 years in adjacent areas, such as southwestern and central Sweden, as shown in Fig. 10. From the limited data available, however, it is difficult to decide whether the earthquake activity in this area represents a release of remnant stresses associated with the actual formation of the Oslo Rift and Oslo Graben, or whether some tectonic movements are still taking place within this area.

Summary

A synopsis has been presented of past and on-going geophysical research directed towards a more profound geodynamic understanding of the Oslo Rift and Oslo Graben and their associated geological manifestations. Until now,

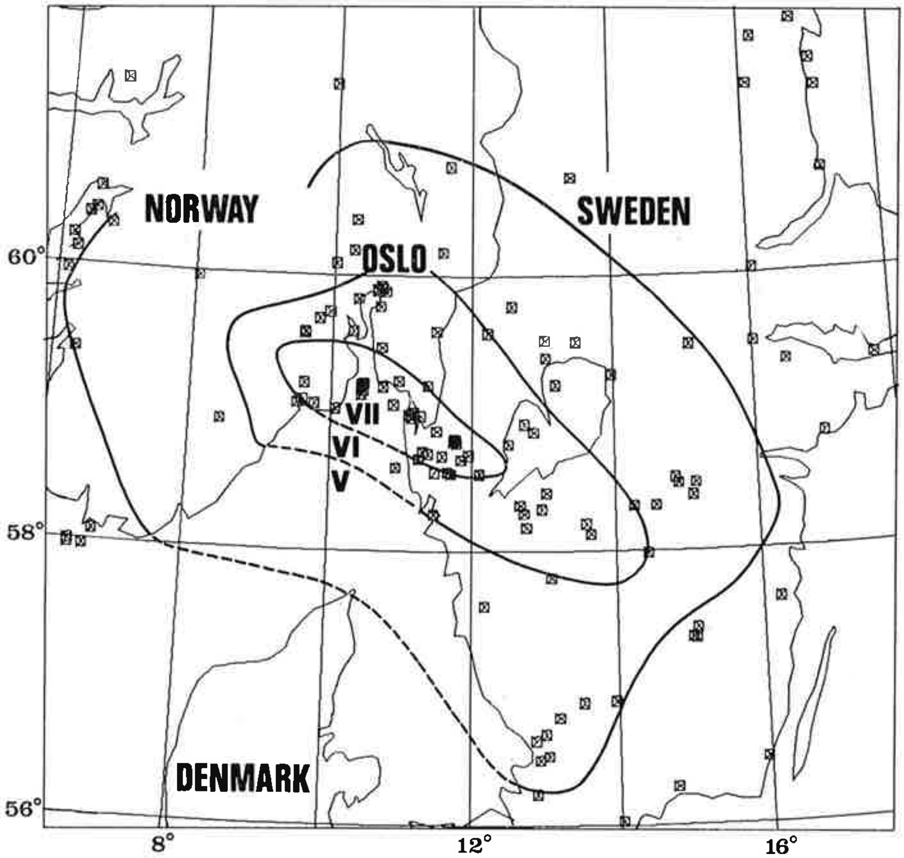
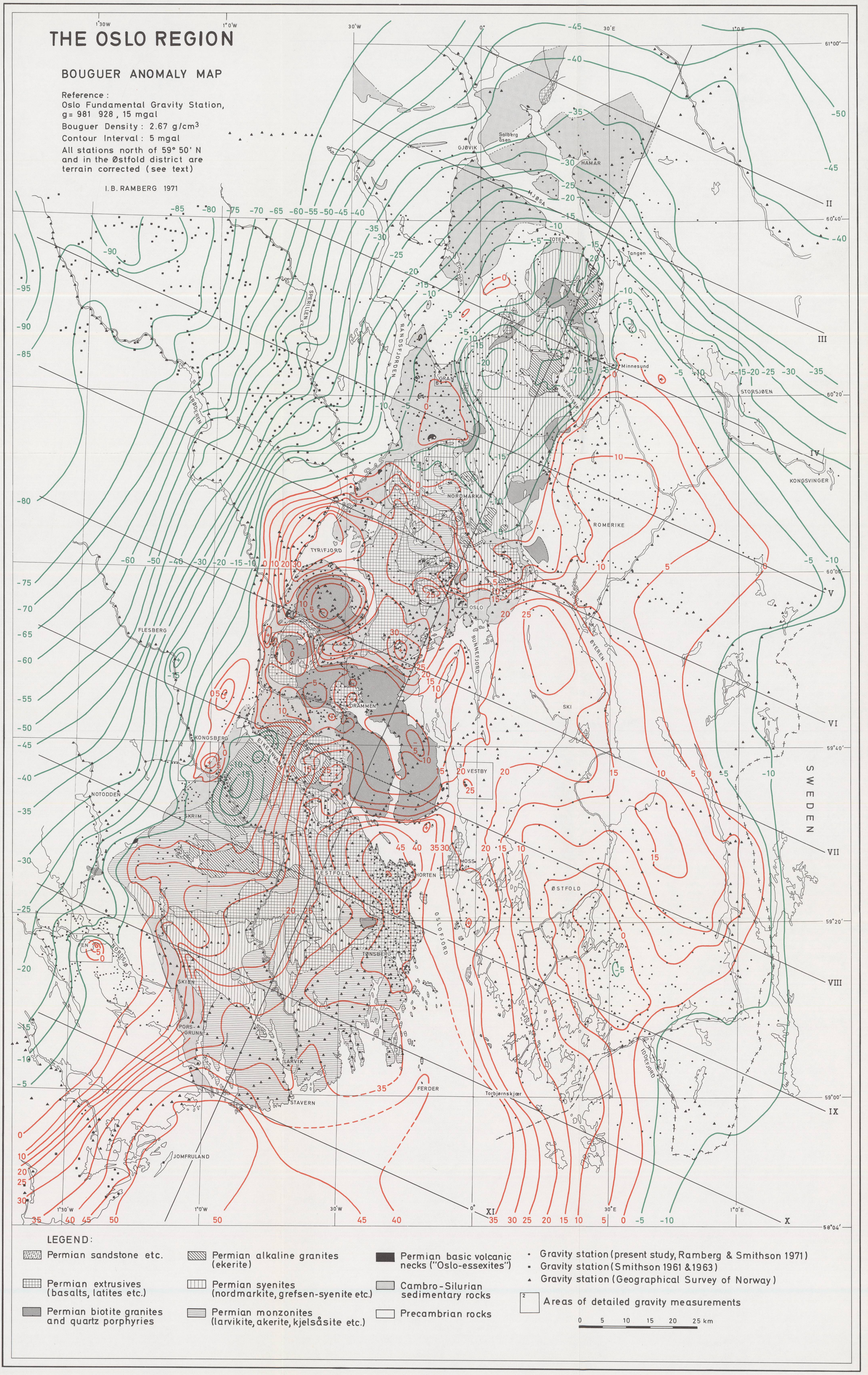


Fig. 10. Isoseismal lines based on the modified Mercally scale for the large outer Oslofjord earthquake of 1904. The surge in earthquake activity in the following 10 yours is indicated by squares for the reported events; these account for roughly 80% of all earthquakes reported in the Oslo Graben proper. The relative precision in epicentre locations is presumed to be around 30 km and thus precludes a detailed correlation between observed seismicity and local tectonics. (Figure redrawn from Husebye et al. 1977.)

gravity and seismological studies (centred on NORSAR research activities) have yielded the most detailed and comprehensive information on the lower crustal parts of this interesting area. As indicated, further geophysical research work is in progress, and the outcome of these studies will hopefully improve and refine current models and dynamical concepts relating to the Oslo Graben in particular and taphrogenesis in general.


THE OSLO REGION
BOUGUER ANOMALY MAP
Reference: Oslo Fundamental Gravity Station, g= 981 928, 15 mgal
Bouguer Density: 2.67 g/cm3
Contour Interval: 5 mgal
All stations north of 59° 50' N and in the Østfold district are terrain corrected (see text)
I. B. RAMBERG 1971
GJØVIK
HAMAR
MJØSA
TOTEN
Tangen
RANDSFJORDEN
SPERILLEN
KRØDEREN
GRAN
Minnesund
HURDALSSJØ
STORSJØEN
KONGSVINGER
NORDMARKA
ROMERIKE
TYRIFJORD
OSLO
FLESBERG
BUNNEFJORD
ØYEREN
DRAMMEN
SKI
KONGSBERG
EIKEREN
VESTBY
NOTODDEN
SKRIM
MOSS
VESTFOLD
HORTEN
ØSTFOLD
OSLOFJORD
TØNSBERG
SKIEN
PORSGRUNN
LARVIK
STAVERN
FERDER
Torbjørnskjær
IDDEFJORD
JOMFRULAND
SWEDEN
LEGEND:
Permian sandstone etc.
Permian extrusives (basalts, latites etc.)
Permian biotite granites and quartz porphyries
Permian alkaline granites (ekerite)
Permian syenites (nordmarkite, grefsen-syenite etc.)
Permian monzonites (larvikite, akerite, kjelsåsite etc.)
Permian basic volcanic necks ("Oslo-essexites")
Cambro-Silurian sedimentary rocks
Precambrian rocks
Gravity station (present study, Ramberg & Smithson 1971)
Gravity station (Smithson 1961 & 1963)
Gravity station (Geographical Survey of Norway)
Areas of detailed gravity measurements
0 5 10 15 20 25 km