A Study of the Earth's Crust in the Island Area of Lofoten–Vesterålen, Northern Norway

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The present study is based on a reinterpretation of seismic refraction data as well as gravity data collected by the Seismological Observatory, University of Bergen in the island area of the Lofoten–Vesterålen, Northern Norway. The study shows a good agreement between the seismic and gravity modelling of the Moho depths along the profile line between the two shotpoints Hamnøy (Lofoten) and Stø (Vesterålen). A maximum Moho-depth of 26 km is observed about 85 km from Stø, and it would seem that the rise of the Moho towards Stø is moderate. On the other hand there is a distinct shallowing of the Moho beneath the Lofoten area.

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Introduction

The crustal structure of the Lofoten–Vesterålen region of Northern Norway was the subject of a special study during the seismic program conducted in the summer 1965 by the U.S. Geological Survey (Branch of Crustal Studies) and the Seismological Observatory, University of Bergen. The Seismological Observatory has since continued to carry out seismic and gravimetric measurements in this island area as well as on the adjacent continental margin. The gravimetric field measurement on land was carried out in 1968 and the deep seismic sounding was further carried out in 1969, 1970 and 1972. The data from the investigations on the Lofoten–Vesterålen islands have been the subject of several M.Sc. theses (Kjenes 1970, Svela 1971, Hansen 1972, Enoksen 1973). Two papers based on the collected data have been published (Thanvarachorn 1975, Sellevoll & Thanvarachorn 1977). The main intention of the present paper is to present the results of a reinterpretation of the available seismic and gravimetric data.

Data acquisition and analysis

The two shotpoints ('Stø' and 'Hamnøy') together with the recording sites are plotted in Fig. 1. The charges were detonated on the sea floor at a dept of 47 m (Stø) and 45 m (Hamnøy). Tables 1a and 1b give information about shotpoint location, shot numbers, date, explosion time and charge size. Seismic signals were detected by a three component geophon system (HS-1/4,5 Hz) and recorded on analogue magnetic tape, together with radio time signals

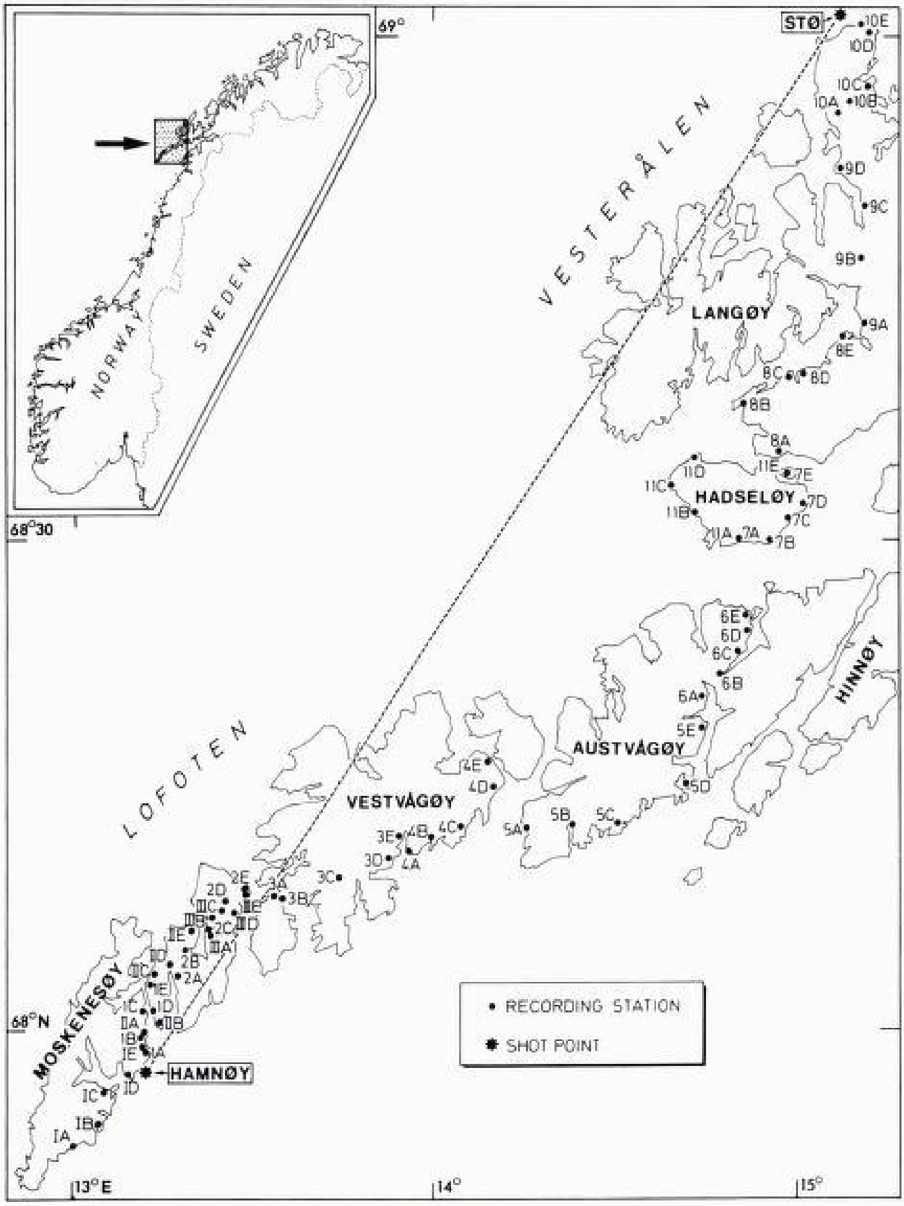


Fig. 1. Location of seismic stations and shotpoints.

(Tryti & Sellevoll 1977). Five recording units (Mars 66, marked A, B, C, D and E) were used during the field measurements and the data obtained were manually digitized. A frequency-analysis (Enoksen 1973) showed that a good signal to noise ratio could be obtained by band-pass filtering between 6 and 16 Hz. After applying this filter the Z-components were plotted in two seismic sections using a reduction velocity of 6 km/sec. The two seismic sections – one for the Hamnøy shotpoint and the other for the Stø shotpoint – are presented in Fig. 2.

Table 1. Shots and shotpoints.

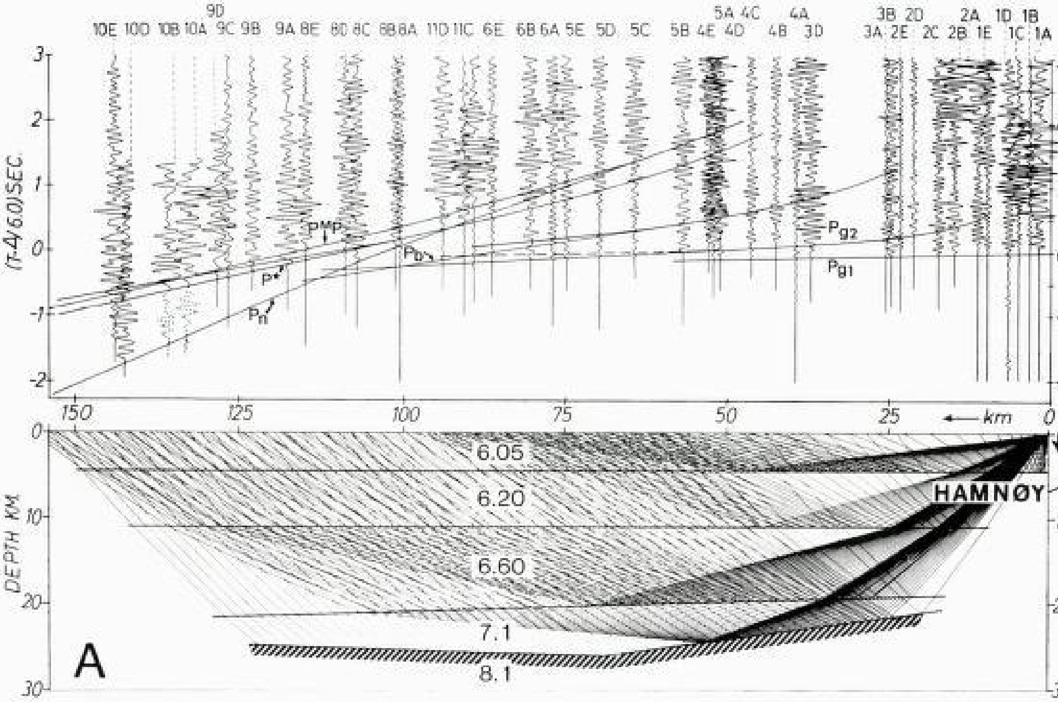
(A) SHOTPOINT: HAMNØY (67°57'42" N, 13°10'12" E) Explosion depth: 45 m)				(B) SHOTPOINT: STØ (69°00'19,2" N, 15°03'23" E) (Explosion depth: 47 m)			
Shot No.	Date	Expl. Time (hms)	Charge (kg)	Shot No.	Date	Expl. Time (hms)	Charge (kg)
1/69	15–8–69	12–28–34.45	(25)	1/70	13–8–70	18–29–32.33	125
2/69	15–8–69	18–29–35.04	(25)	2/70	13–8–70	12–29–53.18	125
3/69	16–8–69		(50)	3/70	12–8–70	12–19–31.72	75
4/69	16–8–69	18–29–34.49	(50)	4/70	12–8–70	18–29–31.34	75
5/69	18–8–69	12–29–34.66	(50)	5a/70	11–8–70	12–29–30.76	75
6/69	18–8–69	18–29–34.34	(75)	5b/70	14–8–70	18–29–32.47	75
8/69	19–8–69	12–29–34.34	(100)	8/70	10–8–70	12–29–32.46	50
9/69	19–8–69	18–29–34.46	(100)	9/70	08–8–70	12–31–55.10	50
10/69	20–8–69	07–59–34.41	(100)	10/70	07–8–70	18–31–57.46	25
				11/70	10–8–70	18–29–31.61	50
10/70	07–8–70	18–29–34.02	100				
9/70	08–8–70	12–29–33.00	100	I/72	31–8–72	18–29–31.92	175
5/70	11–8–70	12–31–31.51	50	II/72	31–8–72	12–29–31.25	150
2/70	13–8–70	12–31–28.95	25	III/72	30–8–72	18–29–31.80	125

Wave pattern, phase correlation and seismic modelling

The first seismic model of the crustal structure of the Lofoten–Vesterålen region was based on seismic records from several large shots fired at a single shotpoint north of the Lofoten–Vesterålen islands (20 km west of Tromsø). A two-layer crust with P-velocities of 6.10 and 6.67 km/s was deduced. The apparent P_n velocity was found to be 8.26 km/s in the distance range 160–290 km from the shotpoint. The elongated gravity high, which is especially well developed in the Lofoten area, was assumed to be mainly a result of crustal thinning (Sellevoll 1967).

Since 1965 new seismic and gravity measurements have been carried out on land in the Lofoten–Vesterålen area. These measurements have given additional information concerning the crustal structure of the Lofoten–Vesterålen island region which in general supported the main feature of the preliminary model based on the 1965 measurements. In the following, a reinterpretation is presented of the data obtained during the 1969–72 seismic investigations in the Lofoten–Vesterålen area. The kinematic seismic modelling has been carried out by application of a ray-tracing program developed by Pajchel (1980).

The P-wave velocity associated with the uppermost part of the crust (P_{g1} in Fig. 2) has been found to be 6.05 km/s. Beyond 25 km from shot-point 'Stø' the P_{g1}-phase seems to disappear and a new strong first onset is clearly observed at a distance of 50–60 km. This supposedly new phase has been designated as P_{g2}. A completely analogous travel-time feature has not been observed on the seismic section from the countershot at shotpoint 'Hamnøy'.



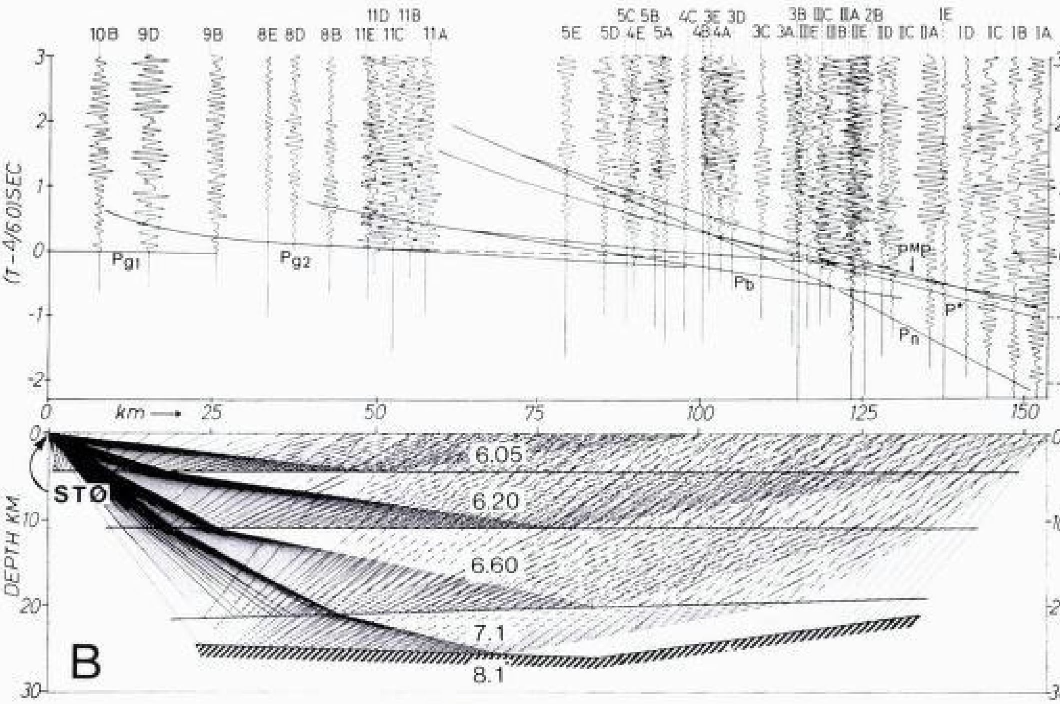


Fig. 2 A and B. Seismic record section for the Hamnøy (A) and Stø (B) shots. Phase correlations and identifications together with ray tracing, layer P-velocities (km/s) as well as the crustal structure are shown on the figure. The Z-components at the stations 10A and B have been destroyed and are partly replaced by the recordings on the NS-components (dashed).

The P_{g1}-phase at this shotpoint, however, is observed beyond 25 km, but certain similarities exist for the P_{g2}-phase from the two shotpoints. The P_{g2}-phase may be explained in several ways, but a preferred interpretation is that the P_{g2}-phase originates from below a thin surface (4–5 km) layer where the P velocity increases from about 6.05 to 6.2 km/s. The data are, however, considered insuffivient for reaching a firm conclusion regarding the structure at the depth interval 4–11 km.

A P-phase (marked P_b), assumed to originate from an intra-crustal discontinuity, is weak but well recorded as the first onset in the seismogram section (Fig. 2 B) between 100 and 120 km from shotpoint 'Stø'. The correlation of the P_b onset for the countershots (Fig. 2 A) is uncertain, but the result obtained indicates an almost horizontal discontinuity at a depth of 11 km and with a phase velocity of 6.6 km/s. This conclusion does not agree with previous interpretations involving an apparent southward shallowing of this discontinuity along the profile in the Lofoten region.

A strong and distinct P-phase, termed P^x, is observed in the seismogram section, Fig. 2 A. A corresponding phase is seen on the seismogram section from the countershot, but this is not so well recorded (Fig. 2 B). The apparent velocities and intercept-times obtained suggest that this phase originates from a layer located at a depth of about 20–22 km in the Vesterålen region. The depth of this layer decreases towards the Lofoten region.

A distinct P_n-phase is observed from shotpoint 'Stø' by the stations located in the Lofoten area (Fig. 2 B). The high apparent velocity of this phase (8.8 km/s) indicates a Moho rising towards the south in the Lofoten area. The correlation of the corresponding P_n-phase (with an apparent velocity of 7.3 km/s) observed from the countershot at 'Hamnøy' can be called into question; but the resulting real P_n-velocity of 8.05 km/s is in agreement with what should be expected. Combining the P_n apparent velocities observed from both shotpoints show that the Moho dips at 5° to the northeast beneath the Lofoten region along the line of profile.

Concerning the Vesterålen region (shotpoint 'Stø') and the correlation of the P_n-phase from the two shotpoints we are unable to draw any definite conclusions about the apparent velocities in both directions from the two shot-points. The observations suggest, however, a weak shallowing of the Moho in a northward direction along the profile (Fig 2).

Discussion and conclusion

The distribution of the shotpoints and recording sites used during these seismic reflection–refraction experiments in the Lofoten–Vesterålen area does not meet the requirement that shot and recording sites should lie on a 'straight line' (Fig. 1). Most of the seismic stations lie on the east side of the straight line between the two shotpoints. The station location 'offsets' are in some cases as much as 30 km. The physical conditions along the real ray paths from the shotpoints to the recording stations may be different from the physical conditions along the shortest line between the two shotpoints (Fig. 1). Such possible variations in physical conditions may change both the kinematic and dynamic wave pattern. The seismic modelling of the crustal structure carried out in the present study is consequently circumscribed by this uncertainty. A normalisation of the seismic recordings shown on Fig. 2 has for various reasons not been possible, and this fact reduces to some extent the reliability concerning the phase correlation as well as the possibilities for detailed seismic amplitude modelling of the crustal structure.

In general the geological-geophysical patterns along the Lofoten–Vesterålen island belt as well as on the adjacent continental shelf (margin) suggest that the underlying continental crust is to some degree segmented into 'blocks' which are observed as basins and crystalline basement highs on the adjacent Lofoten–Vesterålen shelf area. The Lofoten–Vesterålen islands appear to have undergone a rather extensive uplift as compared with the surrounding sedimentary sequences. This differential vertical movement, which has developed faults, is especially well observed as rather strong reflection–diffraction waves on the multichannel seismic sections obtained in the near coastal areas along the Lofoten–Vesterålen islands (Nysæther et al. 1969).

Gravity modelling has been carried out in order to investigate whether the crustal model obtained on the basis of the present reinterpretation of the seismic data is in agreement with the gravity anomaly observed along the Lofoten–Vesterålen islands. The modelling program applied (Hjelle 1979) is a prism-oriented program where the gravity effect from each prism is calculated and added in order to obtain the total gravity value at each point on the surface used in the gravity calculation. The program works in two modes: 1) a direct calculation of the gravity effect from a body where its shape and density distribution are known; 2) an inverse calculation of the shape based on a known gravity anomaly field and density distribution. The last mentioned type of calculation has been applied for the modelling presented here.

The gravity anomaly map which constitutes the basis for the calculation is shown in Fig. 3. The seismic stations and shotpoints are distributed in such a pattern that the gravity edge effect is rather limited (Figs. 1 and 3). The area within the frame in Fig. 3 has been divided into 42 km x 20 km 'units' and the Bouguer anomaly values are estimated for each of the 840 'units'. The depth to each of the layers is assumed to be the same for the whole area as shown on the seismic crustal model presented in Fig. 2. The desities which have been applied for the gravity modelling are assumed constant for each layer, and the densities used are based on the seismic velocities (P-velocities) by application of the following formula (Talwani et al. 1959):

$$\varrho = 1.7 + 0.2\ V_p$$

The seismic crustal model presented in Fig. 2 has no lateral density variation above 18 km and the observed gravity values were reduced by 67 m.gal in order to correct for the masses above this depth (18 km). The gravity effect

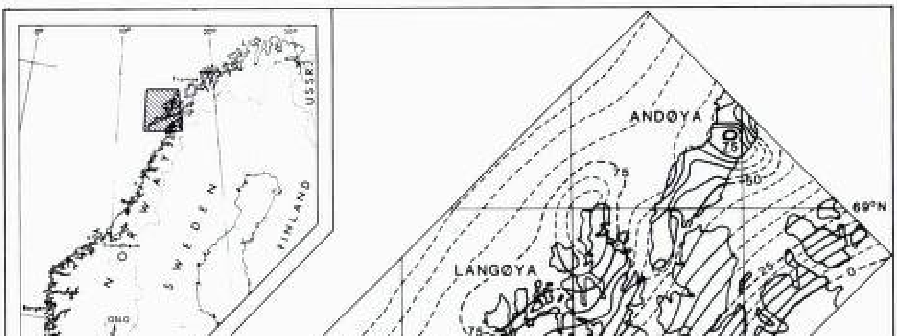


Fig. 3. A Bouguer gravity map for the Lofoten–Vesterålen region. The solid lines are those transferred directly from Svela (1971). The dashed lines are mainly based on the NGO (1963) gravity map.

caused by layer no. 3 below 18 km and by layer no. 4 were then calculated and substracted from the corrected gravity values.

The regional gravity effect was calculated and finally removed, and the gravity residual effect then obtained was utilized for the calculation of the depth of the Moho. The depths of the Moho from the seismic model were used to initiate the gravity modelling. Adjustments to these depths were made in the area to satisfy the residual gravity effect. The computed depths along the central part of the 'profile line' (location of seismic stations and shot-points) are plotted in Fig. 4 (filled circles). The figure shows that the seismic and gravity modelling of the Moho-depths are in good agreement with each other.

Magnetic measurements carried out by the Geological Survey of Norway in the Lofoten–Vesterålen and adjacent regions also show many features of interest. The Lofoten area belongs to a distinctive magnetic high. This can be

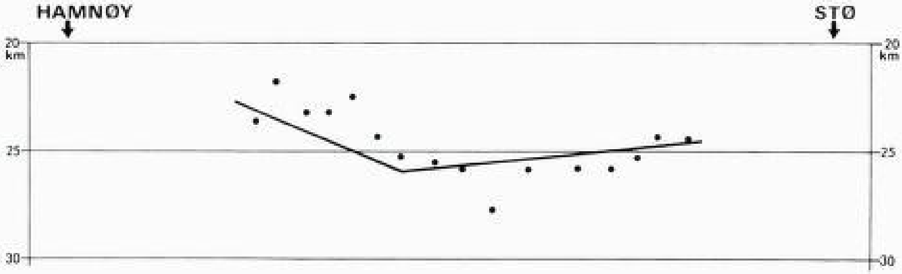


Fig. 4. A correlation of the 'seismic and gravimetric modelling' of the depth to Moho. Solid line – seismic. Dots – gravimetric.

explained by the magnetic properties of the rock, occurring at the surface, if these are considered to extend to a depth of around 20 km (Åm 1975).

Finally attention is drawn to the geological history of the Lofoten–Vesterålen region. The Lofoten–Vesterålen terrain exposes an unusually deep section through the Archaen and Proterozoic crust, the geological history of which (Griffin et al. 1978) has involved repeated vertical movements of considerable magnitude (at least 30 km). There have been two major periods in which new material has been added to the crust, one at ca. 2700 m.y, the other a protracted period from ca. 2100 to 1700 m.y. Important metamorphic events occurred at ca. 2700–2600 m.y, ca. 1830 m.y and ca. 1100–900 m.y Minor heating, intrusion of pegmatites and thrust-faulting occurred during the time of the Caledonian orogeny. Present evidence suggests that Lofoten–Vesterålen formed part of the Baltic plate during the Caledonian orogeny, but escaped deformation because it lay beneath the overriding nappe complex.

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