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Seismic Velocities of Granulites from the Seiland Petrographic Province, N. Norway: Implications for Scandinavian Lower Continental Crust

P.N. Chroston and C.J. Evans

School of Environmental Sciences, University of East Anglia, Norwich, Norfolk, U.K.

Abstract. Compressional and shear wave velocities have been measured in the laboratory at up to 1.0 GPa effective pressure on a suite of granulite facies rocks from the Seiland Petrographic Province. The suite may be of Precambrian age and the measurements were made to test a proposal that the suite represents lower continental crust. Compressional wave velocities at 0.4 GPa effective pressure range from 6.41–6.97 km s^{-1} with a mean of 6.71 km s^{-1}. Measurements of the parameter $\frac{\partial V}{\partial T_p}$ suggest a value of -0.8×10^{-3} km s^{-1} $°C^{-1}$, and the temperature corrected mean velocity of about 6.5 km s^{-1} at 20 km depth is comparable to that found in parts of the lower crust in Scandinavia. The mean Poisson's ratio of 0.29 at 0.4 GPa is slightly higher than that found (0.276), but could be reduced if heterogeneity in the suite and the effect of higher pressures are taken into account. The occurrence of lower continental crust as a thrust slice in the Province is consistent with current ideas on the geological evolution of this area.

Key words: Norway – Seiland – Laboratory measurements – Seismic velocities – Granulites – Lower continental crust

Introduction

Broad constraints for the interpretation of the lower continental crust have been provided by general geological considerations, and by experimental studies on the petrology and physical properties of rocks. It is recognized, for example, that the average compressional wave velocity through the lower crust lies mainly in the range 6.5–7.5 km s^{-1} (Christensen and Fountain, 1975), and that it is likely to be composed of granulites with lesser amounts of igneous rocks ranging in composition from granite (charnockite) to gabbro (pyroxene granulite) (Smithson, 1978). Further, the variability of seismic velocities in refraction studies and the results from deep reflection sounding experiments indicate a heterogeneous lower crustal structure (Smithson et al., 1980).

These constraints have been used by a number of workers in an attempt to interpret suites of exposed rock as lower crust, or even as complete crustal sections. In Britain, for example, Hall and Haddad (1976) and Hall and Simmons (1979) have compared the seismic velocities of the high grade Lewisian gneisses of the N.W. Highlands with the velocities of the lower crustal layer revealed on the LISPB (Bamford et al., 1978) and NASP seismic profiles (Smith and Bott, 1975). Evans (1980) has also compared the properties of the Ox Mountain granulites with the lower crustal velocities of the Midland Valley (Assumpcao and Bamford, 1978). In the Alps, a section across the Ivrea zone has been proposed as a section through the crust (Fountain, 1976), and the seismic velocity structure based on laboratory measurements compared favourably with that obtained from seismic experiments (Choudhury et al., 1971).

In Scandinavia, granulite facies terrains are found both in the Fennoscandian shield and in the Caledonides. The high-grade gneisses of Lofoten-Vesteralen (see e.g. Griffin et al., 1978) are an example of the former, whilst the latter include the granulites of the Jotun nappe (Strand, 1972) and of the Seiland Petrographic Province (Hooper, 1971). So far, however, there has been no systematic study of the physical properties, particularly seismic velocities, of these or other granulite terrains in Scandinavia to enable a comparison with lower crustal properties. In this paper, we describe the results of measurements of the seismic velocities of granulites from the Seiland Petrographic Province, and discuss their implications in the light of a proposal that part of the Province may represent lower continental crust of Precambrian age.

The Seiland Petrographic Province

In order to compare a surface suite of rocks with the deep crust a number of geological constraints have to be satisfied. These include the appropriate metamorphic grade for a deep crustal level, a comparable stratigraphic age, and an adequate explanation for their present (surface) disposition.

The Seiland Petrographic Province (Barth, 1953) shows a complex history of deformation, metamorphism, and igneous intrusive activity. The Province covers the islands of Stjernøy, Seiland, and Sørøy, and much of the Loppen District (Fig. 1), and is believed to be entirely contained within the Kalak nappe complex (Sturt and Roberts, 1978) in the north Norwegian Caledonides. The nappe tectonically overlies the autochthonous Precambrian rocks of the Fennoscandian Shield, which are exposed in tectonic windows in the Caledonides to the south-east of the area. Metasediments (psammites, pelites, marbles and garnet bearing gneisses) of Lower Palaeozoic age (Holland and Sturt, 1970) occur mainly in the west of the Province and

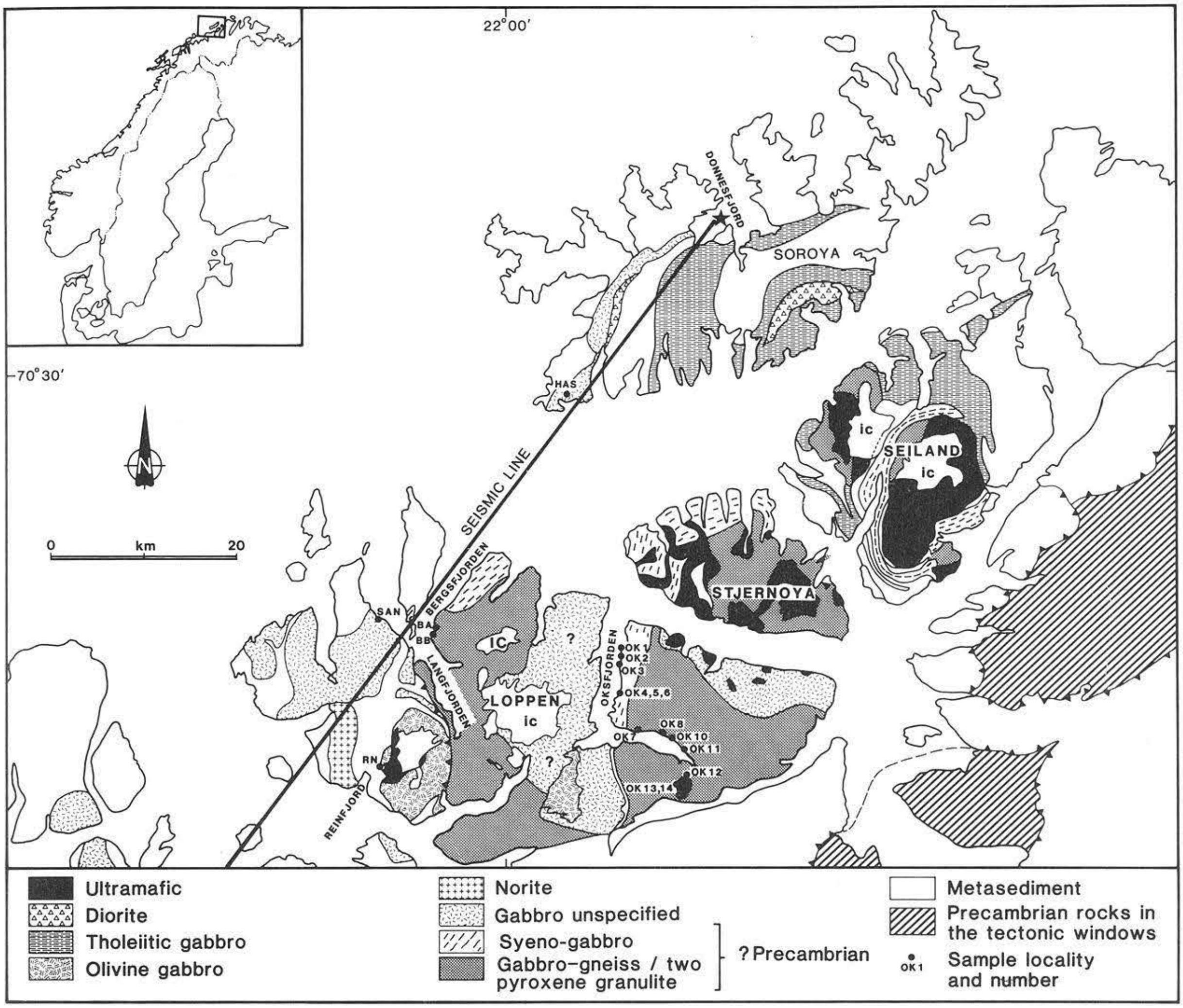

Fig. 1. General geology of the Seiland Petrographic Province, N. Norway, with sampling sites and location of the seismic line

on Sørøy, and in the rest of the area as minor intercalations. Igneous and meta-igneous rocks, however, dominate the area. Gabbros, anorthosites and peridotites with clear igneous textures are found throughout and on Sørøy, Seiland and Stjernøy they were intruded under amphibolite facies conditions, reaching the peak of the metamorphism at about 530 m.y. ago (Pringle, 1971).

The Palaeozoic age of the bulk of the rocks of the Province clearly precludes them from comparison with deep crustal rocks of the Precambrian Shield. However, the extensive area of mafic rock covering the east side of the Loppen District and Stjernøy displays a suite which was clearly metamorphised under granulite facies conditions (Oosterom, 1963; Hooper, 1971; Brueckner, 1973). These rocks have not so far been studied in detail but are believed to consist primarily of a gabbro gneiss complex with some syenite gneiss. The gabbro gneiss complex is dominantly an augite-labradorite gabbro granulite but also includes interlayered olivine gabbro, norite, anorthosite gabbro with garnet biotite gneiss, and amphibolite. In addition, the complex includes smaller unfoliated bodies of gabbro syenite, anorthosite, hornblendite and peridotite (Krauskopf, 1954). An important feature of these rocks is that dating of the foliated mafic granulites (Brueckner, 1973) suggests that some of these gneissic rocks may be of Precambrian age (ca. 1,065 m.y.). Although the results were questioned by Pringle (1975), there is little doubt that at least part of the meta-igneous province may be much older than the Caledonian intrusives, and is more comparable with parts of the Precambrian Shield.

The origin of the Province has been the subject of some controversy. Following the discovery of the positive 100 mgal gravity anomaly associated with it, Brooks (1970) suggested that the rocks of Seiland and Stjernøy represented the top of a mafic-ultramafic culmination under Sørøy and which had been transported by thrusting to the south-east. An alternative suggestion, using the granulite facies metamorphism as evidence, was that the anomaly is essentially due to an upward bulge of the "Conrad" discontinuity, and that the mafic complex may represent lower crust. Many ideas have, however, been based on principles of plate tectonics. Harland and Gayer (1972) suggested that the complex could represent a Caledonian suture, though this was dispelled by Brooks (1971). Ramsay (1973) believed that the vast volumes of mafic and ultramafic rocks indicated an attempt at producing a constructive plate margin and proposed a "stillborn marginal ocean". More conventionally, perhaps, the sedimentation, deformation, metamorphism and igneous intrusions can all be explained as a deep section above an eastward dipping subduction zone

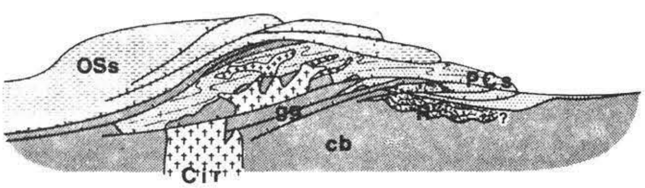

Fig. 2. Diagrammatic profile depicting the tectonic structure of the area of the Seiland Province, northern Norway (after Sturt et al., 1978) (OSs: Ordovician-Silurian sediments; PCs: Precambrian sediments; Cir: Caledonian intrusive rocks; cb: crystalline basement; gg: gabbro gneiss)

at an Andean type continental margin (Robins and Gardner, 1974). Thus, although the province is recognized as one of the most distinctive features of the Caledonian geology of northern Norway, its origin is somewhat uncertain.

The high-grade gabbro gneisses of Loppen and Stjernøy are, however, clearly an integral part of the Province. Their present upper crustal position is essentially due to major (late Caledonian) thrusting (see Fig. 2) and they might, therefore, represent an excellent exposure of lower crustal rocks, perhaps typical of at least part of the Fennoscandian Shield. The prime objective of this paper is to compare

Table 1. Mineralogy and texture of the samples studied. (Key: PF, plagioclase feldspar; Opx, orthopyroxene; Cpx, clinopyroxene; Amp, amphibole; Bio, biotite; Op, opaques; apat, apatite; qtz, quartz; sph, sphene; ol, olivine; serp, serpentine; tr, trivial; gs, grain size)

Sample No.	PF	Opx	Cpx	Amp	Bio	Op	Other	Texture
Gabbro gneisses (granulites)								
OK1	26		2	68	4		tr, apat	gs 0.5 mm, granoblastic but weak foliation, mortar texture on grain boundaries
OK2	59		24		17			gs 0.25–1 mm, granoblastic but moderate foliation defined by mica
OK3	60		tr	23	16	1		gs 0.5–1 mm, granoblastic but moderate foliation defined by mica and amphibole or feldspar rich bands. Plag shows bent twinning, extensive mortar texture on grain boundaries
OK4	16		26	39	11	8	tr, qtz	gs 0.1–1 mm, rounded porphyoclasts of plag, amp and pyx in fine grained mortar texture. Moderate foliation defined by amphibole. Bent twinning in plag
OK5	63	16	13	1	1	6		gs 0.5–2 mm, granoblastic but partially mylonized to give thin strings of mortar texture. Plag deformed, weak foliation
OK6	30		23	45	1	1		gs 0.5 mm. Virtually undeformed granoblastic rock, some bent twinning in plag
OK7	66	6	11	6	1	10	tr, sph	Relict coarse porphyroclasts of plag, in polygonal granoblastic texture. No foliation.
OK8	42	12	23	11	tr	11	ap. 1	gs 0.1 mm but relict porphyroclasts of pyx up to 2 mm. Strong foliation defined by feldspar and pyx rich bands with granoblastic texture
OK10	33		12	46		9		Intensely mylonized rock. Strong foliation defined by plag lenses in granoblastic amp. rich material (0.2 mm) highly altered, some relict porphycroclasts of cpx (3 mm)
BA2	38	4	28	1	19	10		gs 0.25–1 mm, granoblastic, unfoliated
BB1	43	2	9	24	15	7		gs 0.25–1 mm, granoblastic with weak foliation defined by feldspar and pyx rich bands, trace of mortar texture
BB3	44	3	24	10	15	4		0.25 mm granoblastic aggregate of pyroxene, foliation defined by mica and amp. orientation and by feld. and pyx. rich bands
BB4	50	10	14	13	11	2		gs 0.25 mm, granoblastic aggregate of pyroxene, weak foliation defined by mica and amp. orientation
Gabbros								
HAS4	53	16	25	tr		6		gs 0.5–1 mm, no foliation, igneous texture
SAN1	49	11	30		2	4	Chl 4	gs 0.5–1 mm, igneous texture, some alteration with chlorite veins.
SAN2	52	10	33		2	2	Chl 1	gs 0.5–1 mm, igneous texture, minor alteration
Ultramafics								
RN7	1	32	57			1	Ol 7 Serp 2	Large crystals pyx (1–3 mm) with minor plag (0.1 mm), igneous texture, no foliation
OK12	2	1	67	6		5	Ol 14 sph 5	Large crystal pyx and Ol (2–3 mm), no foliation, igneous texture, little alteration

the seismic properties of this mafic suite with the lower crust of the Shield.

Selection of Samples

Samples have been collected from both the gabbro gneiss complex, and for comparative purposes, from the Caledonian intrusives (Fig. 1). For the latter, samples were taken from the Hasvik gabbro on Sørøy, from the Sandlands-Middagsfjell gabbro, and from ultramafic intrusions in Øksfjord and Reinfjord (Fig. 1). Within the mafic gneiss complex, nearly all of the samples collected were of gabbro-granulites which dominate the complex. The samples were taken from the pyroxene granulite on the east side of Bergsfjord (Hooper, 1971) from Krauskopf's (1954) "gabbro gneiss I" complex on the east side of Øksfjord (gabbro gneiss in Fig. 1) and from his "gabbro gneiss III" complex (syenite gabbro in Fig. 1). The "gabbro gneiss I complex" is chiefly composed of augite-labradorite gabbro granulite. It is probably comparable with the two-pyroxene granulite found on the east side of Bergsfjord and with similar rocks on Stjernøy, and appears from the geological map (Norges Geologiske Undersøkelse, 1974) to dominate the whole mafic gneiss complex. The "gabbro gneiss III" complex occurs down the east side of Øksfjorden and here, the gabbro gneiss is interlayered with garnet biotite gneiss, amphibolite and pyroxene-plagioclase-hornfels (Krauskopf, 1954). The gabbro gneiss complex is clearly heterogeneous and a full representative collection could not be taken, and the samples selected represent essentially varieties of the dominant pyroxene-granulite lithology. The mineralogy of the samples is shown in Table 1. All of the samples from the gabbro-gneiss complex show a primary granulite-facies mineralogy and granoblastic texture, and most show varying degrees of retrogressive metamorphism. Sample OK-5, for example, shows small amounts of amphibole and sample OK-1 is now effectively an amphibolite, with no primary pyroxene present. In addition most samples show signs of secondary deformation, with deformed plagioclase and some cataclasis, perhaps due to its uplift end emplacement during the evolution of the Seiland Province.

Method

Cores of 25 mm diameter were taken from the samples and were cut with smooth perpendicular ends to a length of approximately 25 mm. Two cores were taken from most rocks, one parallel to the foliation and one perpendicular to it. In some cases, a 25 mm core was redrilled to give a 16 mm diameter core at right angles to the larger core. Compressional and shear wave velocities were measured at the University of East Angia (UEA) and the University of Washington (UW) using a pulse transmission method similar to that of Birch (1960). At the University of East Anglia, lithium niobate compressional and shear wave transducers were used, operating at a frequency of 1 MHz. The latter transducers give a good shear wave arrival with a smaller compressional wave forerunner. Transit times were measured using a Hewlett-Packard timer-counter (linked to an oscilloscope) and after corrections for sample compressibility and transducer delay compressional wave velocities could be measured to an absolute accuracy of better than 2% and shear wave velocities to better than 5%. Plexol oil was used for the confining pressure medium and a maximum pressure of 0.4 GPa could be attained. All the samples were saturated in 0.5 M NaCl solution and pore water pressure equal to atmospheric pressure was used throughout. Measurements at the University of Washington used a similar system, but separate measurements of compressional and shear wave velocities were made using PZT-5 transducers for the compressional wave measurements and AC-cut quartz transducers for the shear wave measurements. The samples were screened in copper mesh to allow any pore fluid under pressure to escape. Both compressional and shear wave velocities could be measured to an accuracy of 2%.

On the UEA system, velocities were measured with increasing confining pressure at intervals of 0.025 GPa up to the maximum confining pressure (0.4 GPa) and then with decreasing pressure to (virtually) atmospheric pressure. On the UW system, velocities were measured at 0.02 GPa intervals at up to 0.1 GPA and then at 0.1 GPa intervals up to 1 GPa confining pressure. There was nearly always close agreement (± 0.05 km s^{-1}) between velocities on the increasing and decreasing part of the cycle at pressures above 0.2 GPa.

Seismic Velocities Across the Mafic Complex and Comparison with Lower Crustal Velocities

The potentially complex nature of the lower continental crust (Smithson, 1978) makes the seismic velocity of a particular rock type of only limited value, and in order to make a meaningful comparison with the field seismic velocities, an effective mean velocity for the complex needs to be calculated. This mean velocity can be calculated from in situ velocity measurements or from estimating the proportions of the different rock types involved and whose individual velocities are known from laboratory measurements.

There are, however, difficulties with the former method. In particular, short seismic lines (a few hundred metres long) on complexes at or near the surface may give low velocities because the low confining pressures may leave cracks open, although Smithson and Shrive (1975) found a good comparison between laboratory velocities and those measured from seismic lines some 1,150 m long. Ideally, much longer lines are required to acquire velocities from rocks at greater depth where the influence of cracks on the seismic velocities is small. In 1972, a simple seismic refraction line some 200 km long was made across the western part of the Province to investigate the upper crustal structure of this area. Shots were fired from Donnesfjord (on the northern side of Sørøy) and from Lyngenfjord, about 100 km to the south-west of the Province (Chroston et al., 1976). The shots from Donnesfjord were also recorded on the east and south-east side of the mafic complexes of Stjernøy and Seiland. However, interpretation of the arrivals appeared to show no increased velocity through these areas compared to the velocity of the metasediments (6.18 km s^{-1}). Such a result is consistent with the interpretation (Brooks, 1970; Chroston, 1974) that the mafic rock extends only to shallow depth, being truncated by the major thrust which outcrops to the south-east. The analysis in this paper therefore is based only on the laboratory measured velocities.

The results of the laboratory measurements are shown in Table 2 and Table 3 summarizes the velocities and elastic properties at a confining pressure of 0.4 GPa and 1.0 GPa. The "gabbro-gneisses" show a wide range of velocities at 0.4 GPa, from 6.41–6.97 km s^{-1} (mean 6.71 km s^{-1}), and with Poisson's ratios from 0.24 to 0.33 (mean 0.29). Some of the samples are significantly anisotropic. The sample OK-1, for example, shows a difference between the two cores of 0.43 km s^{-1} at 0.4 GPa. This can, however, be entirely explained by the difference in density between the cores. Anisotropy in other samples is not so strong, but in some cases is slightly greater than differences due to possible measurement error, and the velocities from field seismic experiments over this rock suite could vary significantly with propagation direction.

The few gabbros measured also give a wide range of velocities 6.56–7.22 km s^{-1}. Shear wave velocities could only be measured on samples from the Sandlands-Middagsfgell gabbro. The high Poisson's ratios (ca. 0.30) are consistent with other workers' measurements on gabbroic rock (e.g. Birch, 1961). As might be expected, ultramafic rocks give the highest velocities (up to 7.96 km s^{-1}) and the mean of these samples would be expected to be higher for fresh samples.

The data show that in nearly all cases the increase in compressional and shear wave velocities is less than 0.1 km s^{-1} between 0.4 GPa and 1.0 GPa, and that the change in Poisson's ratio is not more than 0.02. This increase in velocity due to pressure is likely to be counteracted by temperature effects. Temperature effects on compressional wave velocities have been measured by a number of workers (Hughes and Maurette, 1957; Kroenke et al., 1978; Stewart and Peselnick, 1977; Kern, 1978) and a study of their results shows a considerable divergence of the parameter $\left(\frac{\partial V}{\partial T_p}\right)$. A systematic study by Christensen (1979) suggested a value of about -0.59×10^{-3} km s^{-1} °C^{-1}. We have also measured the effect on some of the Seiland Province rocks, and the results are shown in Fig. 2. The confining pressure was held at 0.4 GPa and the temperature increased (over a period of 12 h) to 250° C and then reduced, with velocity measurements made at 25° C intervals. Only the decreasing part of the thermal cycle is shown in the diagram as transient

Table 2. Compressional and shear wave velocities (km s^{-1}), corrected for dimension changes

Sample	Core	Propagation*	Bulk Density ($\times 10^3$ kg m^{-3})	0.04 GPa		0.1 GPa		0.2 GPa		0.4 GPa		0.6 GPa		0.8 GPa		1.0 GPa	
				V_p	V_s	V_p	V_s	V_p	V_s	V_p	V_s	V_p	V_s	V_p	V_s	V_p	V_s
Gabbro gneisses																	
OK1	1	X	3.01	6.05	–	6.36	–	6.60	–	6.75	–	–	–	–	–	–	–
	2	Z	2.87	6.01	–	6.07	–	6.16	–	6.32	–	–	–	–	–	–	–
OK2	1	X	3.05	6.39	3.60	6.52	3.67	6.61	3.72	6.68	3.75	6.71	3.77	6.74	3.79	6.74	3.79
	2	Z	3.08	6.27	3.33	6.36	3.42	6.44	3.48	6.52	3.54	6.54	3.58	6.56	3.61	6.56	3.62
OK3	1	X	2.88	6.21	3.12	6.34	3.21	6.45	3.28	6.60	3.45	–	–	–	–	–	–
OK4	1	X	2.95	6.56	3.39	6.64	3.47	6.74	3.55	6.82	3.65	6.85	3.70	6.90	3.73	6.90	3.74
OK5	1	Z	3.01	6.37	3.41	6.54	3.53	6.62	3.55	6.68	3.63	6.71	3.74	6.74	3.89	6.73	3.93
	2	X	2.80	6.25	3.37	6.33	3.45	6.38	3.52	6.34	3.55	6.47	3.60	6.50	3.62	6.41	3.62
OK6	1	X	3.03	6.69	3.62	6.80	3.75	6.89	3.84	6.97	3.92	7.01	3.98	7.03	4.01	7.04	4.01
OK7	1	Z	2.99	6.70	3.43	6.79	3.49	6.87	3.54	6.91	3.59	6.93	3.61	6.93	3.62	6.94	3.64
	2	X	2.91	6.75	3.55	6.82	3.60	6.86	3.63	6.89	3.66	6.90	3.69	6.92	3.71	6.93	3.72
OK8	1	X	3.16	6.41	3.56	6.62	3.71	6.76	3.75	6.91	3.79	–	–	–	–	–	–
OK10	1	Z	3.11	6.65	3.61	6.86	3.67	6.94	3.72	7.01	3.79	7.44	3.82	7.33	3.84	7.18	3.85
	2	X	3.11	6.52	3.44	6.61	3.52	6.69	3.58	6.77	3.66	6.84	3.71	6.86	3.74	6.87	3.76
	3	Z	3.03	6.82	3.69	6.88	3.74	6.95	3.78	7.00	3.81	7.05	3.33	7.07	3.84	7.10	3.85
BA2	1	Z	3.03	6.17	3.67	6.24	3.46	6.40	3.53	6.45	3.58	6.45	3.63	6.47	3.65	6.46	3.65
	2	X	3.04	6.16	3.65	6.30	3.71	6.37	3.75	6.45	3.78	6.48	3.80	6.50	3.83	6.52	3.84
	3	X	3.01	6.23	3.36	6.33	3.48	6.45	3.53	6.59	3.60	–	–	–	–	–	–
BB1	1	X	3.05	6.10	3.52	6.22	3.67	6.35	3.73	6.41	3.75	–	–	–	–	–	–
BB3	1	Z	3.04	6.31	3.36	6.54	3.47	6.73	3.50	6.95	3.53	–	–	–	–	–	–
BB4	1	X	3.13	6.55	3.42	6.64	3.50	6.71	3.56	6.87	3.58	–	–	–	–	–	–
Gabbros																	
HAS4	1		2.89	7.02	–	7.08	–	7.16	–	7.22	–	–	–	–	–	–	–
SAN1	1		3.04	6.79	3.56	6.86	3.61	6.92	3.62	6.95	3.63	–	–	–	–	–	–
SAN2	1		3.02	6.21	3.10	6.37	3.40	6.45	3.48	6.56	3.50	–	–	–	–	–	–
Ultramafics																	
RN7	1		3.29	7.65	4.57	7.78	4.57	7.81	4.57	7.96	4.57	–	–	–	–	–	–
OK12	1		3.27	7.33	3.58	7.42	3.68	7.51	3.70	7.70	3.74	–	–	–	–	–	–

* X: Parallel to foliation, Z: perpendicular to foliation

Table 3. Elastic constants calculated from mean V_p, V_s and ρ

Sample	Pressure GPa	P $\times 10^3$ kg m^{-3}	Mean V_p km s^{-1}	Mean V_s km s^{-1}	V_p/V_s	σ	$\varnothing$ (Km s^{-1})^2	K GPa	μ GPa	E GPa	λ GPa
OK2	0.4	3.08	6.60	3.65	1.81	0.28	28.50	79.5	41.0	105.1	52.1
	1.0	3.10	6.67	3.71	1.80	0.28	26.14	81.0	42.7	108.9	52.6
OK3	0.4	2.88	6.60	3.45	1.91	0.31	27.69	79.8	34.3	89.8	56.9
OK4	0.4	2.96	6.82	3.65	1.87	0.30	28.75	85.1	39.4	102.5	58.8
	1.0	2.98	6.90	3.74	1.84	0.29	28.96	86.3	41.7	107.7	58.5
OK5	0.4	2.92	6.51	3.59	1.81	0.28	25.20	73.6	37.6	96.5	48.5
	1.0	2.94	6.57	3.78	1.74	0.25	24.11	70.9	42.0	105.2	42.9
OK6	0.4	3.04	6.97	3.92	1.78	0.27	28.09	85.4	46.7	118.5	54.3
	1.0	3.07	7.04	4.01	1.76	0.26	28.12	86.3	49.4	124.4	53.4
OK7	0.4	2.96	6.90	3.63	1.90	0.31	30.04	88.9	39.0	102.1	62.9
	1.0	2.98	6.94	3.68	1.89	0.31	30.10	89.7	40.4	105.3	62.8
OK8	0.4	3.17	6.91	3.79	1.82	0.28	28.60	90.6	45.5	117.0	60.3
OK10	0.4	3.10	6.93	3.75	1.85	0.29	29.27	90.8	43.6	112.7	61.7
	1.0	3.12	7.05	3.82	1.85	0.29	30.25	94.4	45.5	117.6	64.0
BA2	0.4	3.05	6.50	3.65	1.78	0.27	24.49	74.7	40.6	103.2	47.6
	1.0	3.08	6.49	3.75	1.73	0.25	23.37	72.0	43.3	108.2	43.1
BB1	0.4	3.07	6.41	3.75	1.71	0.24	22.34	68.6	43.2	107.0	39.8
BB3	0.4	3.05	6.95	3.53	1.97	0.33	31.69	96.7	38.0	100.8	71.3
BB4	0.4	3.14	6.87	3.58	1.92	0.31	30.12	94.5	40.2	105.8	67.7
SAN1	0.4	3.05	6.95	3.63	1.91	0.31	30.73	93.7	40.2	105.5	66.9
SAN2	0.4	3.03	6.56	3.50	1.87	0.30	26.70	80.9	37.1	96.6	56.2
RN7	0.4	3.30	7.96	4.57	1.74	0.25	35.51	117.2	68.9	172.9	71.3
OK12	0.4	3.28	7.70	3.74	2.06	0.35	40.64	133.4	45.8	123.3	102.9

σ, Poisson's ratio; $\varnothing$, seismic parameter; K, bulk modulus; μ, shear modulus; E, Young's modulus; λ Lamé's constant

effects are likely to be negligible (Evans et al., 1978). The average gradients of -0.8×10^{-3} km s^{-1} °C^{-1} are higher than those found by Christensen (1979). Assuming a thermal gradient of about 10° C km^{-1}, a reduction in velocity of about 0.12 km s^{-1} at 15 km depth (0.26 GPa effective pressure) and about 0.24 km s^{-1} at 30 km depth would be expected. The effect of temperature on shear wave velocities is uncertain, and the assumption is made that Poisson's ratio is not significantly effected.

All of the velocities of the samples from the "gabbro gneiss complexes" are within the range of velocities observed for the lower continental crust (Christensen and Fountain, 1975). In Scandinavia, earlier seismic refraction experiments suggest a simple two-layer crust (Sellevoll, 1973). Upper crustal velocities range from 6.0–6.3 km s^{-1}, and lower crustal velocities from 6.5–6.8 km s^{-1}. In some areas, a higher velocity of about 7.1 km s^{-1} has also been determined at the base of the crust. In northern Norway, the one seismic line across the Province obtained uncertain P^* arrivals giving a crudely estimated lower crustal velocity of 6.9 km s^{-1} (Chroston et al., 1976).

Some caution should, however, be applied in using these velocities. The quality of the seismic experiments varies considerably, with only more recent ones producing detailed recording with multiple coverage of the line. In addition, modern interpretation techniques, when applied to older data, may modify the crustal model. The results of the Blue Road Project (Lund, 1979) suggest low velocity layers in the upper crust in the vicinity of the Caledonides with, over the Precambrian Shield, a gradational change in velocity across the "Conrad discontinuity" and significant velocity gradients in the upper and lower crust. A comparison of one of the Blue Road profiles and an interpretation of Lofoten-Vesteralen data (Sellevoll and Thanvarachorn, 1977) and with the laboratory results is shown in Fig. 3. Here the laboratory variations with pressure have been translated into velocity-depth functions assuming the effective pressure law (effective pressure = confining pressure − pore water pressure) and also assuming an average crustal density of 2,800 kg m^{-3} and that the pore water pressure is hydrostatic. The Blue Road lower crustal velocities are significantly higher than the mean of laboratory velocities, especially when temperature is taken into account, and in this case the lower crust would have to be significantly more mafic on average than the Seiland rocks to explain the discrepancy. The lower crustal velocity from Lofoten-Vesteralen, however, compares favourably with the mean of the Seiland suite. In general the estimated velocity of the mafic gneisses is in accord with lower crustal velocities on the Shield.

All of the velocities discussed above are compressional wave velocities and it is unfortunate that good shear wave velocity estimates have not generally been obtained for the Scandinavian refraction lines. An estimate of the average shear wave velocities for the upper and lower crust has, however, been made in Sweden for earthquake epicentre determinations (Båth, 1971). For the upper crust, a shear wave velocity of about 3.58 km s^{-1} and a Poisson's ratio

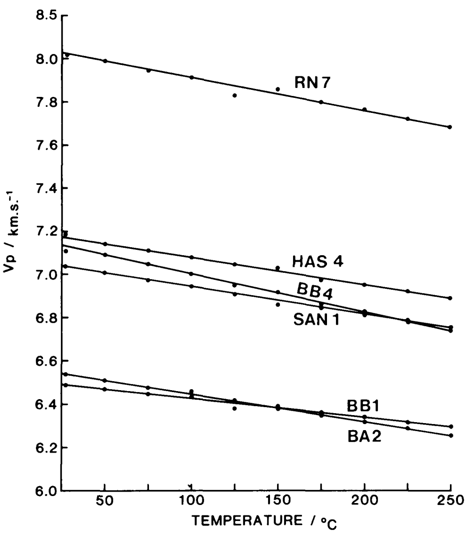

Fig. 3. Effect of temperature on compressional wave velocities on selected samples. All velocities are measured at an effective pressure of 0.4 GPa

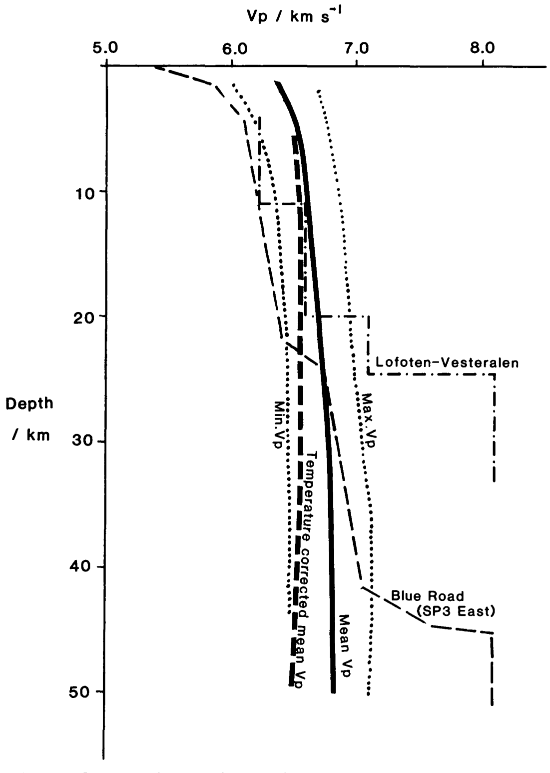

Fig. 4. Comparison of velocity depth profile based on the laboratory data with the Lofoten-Vesteralen profile and a Blue Road velocity depth profile. Possible temperature effects on the laboratory velocities are also shown

of 0.256 has been calculated. For the lower crust, the average shear wave velocity was 3.69 km s^{-1} and the Poisson's ratio 0.276.

This latter value is smaller than the mean of the Poisson's ratio of the granulites, though it is within the range of the calculated values. Two other factors, however, would result in a lower mean Poisson's ratio for the complex. Firstly, the Poisson's ratio decreases with increased pressure, and calculations on the velocity data show that a reduction of the ratio up to 0.03 is found between the effective pressures of 0.4 GPa and 1.0 GPa. Secondly, the lithologies sampled do not include the quartz rich layers which were reported by Krauskopf (1954), both of which would reduce the overall Poisson's ratio. The proportion of these rocks is believed to be minor, however, and their effect may be offset by the presence of anorthosite (with a Poisson's ratio of about 0.30). Taking these factors into account, the overall Poisson's ratio of the granulite samples is very similar to that found for the lower crust.

Discussion

The geology, petrology and physical properties of the mafic gneiss complex as displayed in the Loppen District appear to satisfy well the constraints established for the identification of lower continental crust, and the complex has many similarities to the model proposed by Smithson and Brown (1977). The rocks are dominantly pyroxene granulites, but minor amounts of syenite gneiss, syenite, garnet syenite, amphibolite, and anorthosite are present, as well as garnet-biotite gneiss. The heterogeneous geology is in accord with the results of deep reflection experiments (Smithson et al., 1980). In the area the rocks have crystallized in the granulite facies (Hooper, 1971; Brueckner, 1973) and the estimated mean compressional wave velocity across the mafic gneisses based on laboratory measurements is comparable with the lower crustal velocities from Scandinavia.

The principal problem, however, concerns the tectonic emplacement of the proposed crustal suite, particularly in the light of the varying hypotheses on the origin of the Province. Assuming the suite is of Precambrian age, then one might expect to find a tectonic discountunity between it and the surrounding Palaeozoic sediments and Caledonian intrusions. Such a structure may exist in the Loppen District, where west of Langfjord, metasediments and gabbro are thrust over pyroxene granulites (Hooper, 1971 and pers. comm.), but we are not aware if a comparable structure has been revealed to the east of the mafic suite.

In his interpretation of the 100 mgal gravity anomaly over the Province, Brooks (1970) provided two basic model interpretations of the anomaly. In the first, described above, it could be explained by an upward bulge of the "Conrad" discontinuity and/or a Moho bulge, and the mafic/ultramafic complex represents the sliced-off top of the bulge. In the second, one could also model the anomaly by extending the surface complex down to the NW so that effectively it represents a major thrust wedge of mafic rock. Detailed gravity surveys over the Loppen District (Chroston, 1974) lends some support for the former model, but the emplacement of the complex may be explained reasonably by either. Indeed, the latter model has some similarities to that suggested for the lower crustal rocks of the Jotun nappe (Smithson et al., 1974). It is emphasised, however, that although this suite appears to satisfy both the geological and geophysical constraints for deep crustal rocks, they may not be representative of the lower crust of the entire shield area. The variation in velocities found on refraction lines suggests a significant lithological variation, and measurements of velocities of suites from Lofoten-Vesteralen and from the Jotun nappe, which are currently in progress, should provide further information on this problem.

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