Constitution of the Lower Continental Crust Based on Experimental Studies of Seismic Velocities in Granulite

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ABSTRACT

Rocks of the granulite facies have been proposed as major constituents of the lower continental crust. To evaluate this possibility, compressional and shear wave velocities have been determined to pressures of 10 kb for 10 granulite samples, thus enabling comparisons of seismic data for the lower crust with the velocities and elastic properties of granulite rocks. The samples selected for this study range in composition from granitic to basaltic, with bulk densities of 2.68 to 3.09 g/cm³. At 6 kb, compressional (V_p) and shear (V_s) wave velocities range from 6.39 to 7.49 km/sec and from 3.36 to 4.25 km/sec, respectively. Velocities in granulite rocks are shown to vary systematically with variations in mineralogical constitution. Both V_p and V_s increase with increasing pyroxene, amphibole, and garnet. Velocities increase with an increasing ratio of pyroxene to amphibole in hornblende-granulite subfacies rocks of approximately equivalent chemical compositions. Decreasing quartz content in granulite rocks produces an increase in V_p and an accompanying decrease in V_s, thereby significantly changing Poisson's ratio. The range of velocities measured for the granulite samples is similar to the range of seismic velocities reported for the lower continental crust; thus, the hypothesis that granulite rocks are major lower crustal constituents is further strengthened. Furthermore, it is shown that lower crustal composition is extremely variable, and therefore valid discussions of composition must be limited to specific regions where seismic velocities are well known. The use of seismic velocities in estimating lower crustal composition is illustrated for the Canadian Shield in Ontario and Manitoba. *Key words: crustal structure, Canadian Shield.*

INTRODUCTION

During the past two decades, extensive efforts have been made by seismologists to decipher the structure and seismic velocity distribution within the continental crust. In spite of these efforts, little progress has been made in forging petrologic interpretations of crustal composition from seismic data. The delineation of the crust of the continents into a "granitic" layer overlying a "basaltic" layer by Jeffreys (1926), in fact, still pervades modern literature of explosion seismology (for example, Roller and Healy, 1963; Hill and Pakiser, 1966; Ocola and Meyer, 1972). Russian seismologists (Kosminskaya and Riznichenko, 1964), however, argue that the apparent seismic layering of the continental crust is due to horizontal "metamorphic fronts." This suggestion is very appealing, because lower crustal hydrostatic pressures of 6 to 10 kb and temperatures of as much as 700°C at the Mohorovičić discontinuity (Lachenbruch, 1970) can combine to provide an appropriate environment for high-grade metamorphism. A straightforward application of these pressure-temperature conditions to conventional metamorphic-facies diagrams (Hietanen, 1967; Turner, 1968) indicates that the rocks of the lower crust may be in the granulite facies.

Granulite-facies rocks are abundant within stable Precambrian shield areas and, to a much lesser extent, are components of younger orogens (see Oliver, 1969, for review). The widespread occurrence of granulite in the shield areas is attributed to extensive denudation coupled with tectonic activity to expose lower levels of continental crust. On the basis of this argument, den Tex and Vogel (1962) suggested that the granulite terranes of Cabo Ortegal in Spain represent unroofed lower continental crust. Lambert (1971) argued for a similar lower crustal origin for the granulite terranes of the Yilgarn Block and the Musgrave Range of Australia. In a comprehensive discussion of the setting, metamorphic associations, and general mineralogy and composition of granulite-facies rocks, den Tex (1965) concluded that within the crust there is a gradual transition from rocks of a granitic series (including hydrous migmatite and high-temperature metamorphic rocks) to rocks of the granulite facies, the latter being the major constituent below the Conrad discontinuity. He estimated a lower crustal composition of 50 percent acidic granulite and intermediate charnockite and 50 percent mafic granulite and eclogite.

Another occurrence of granulite-facies rocks is as xenoliths in diatremes, which have long been subject to scrutiny because the eclogite and peridotite xenoliths in them are commonly thought to be samples of the upper mantle. Granulite-facies rocks have also been reported in diatremes in San Juan County, Utah (McGetchin and Silver, 1972), northeastern Arizona (Watson and Morton, 1969), Riley County, Kansas (Brookins and Wood, 1970), Delegate, Australia (Lovering and White, 1969), and South Africa (Wagner, 1928). The close association of granulite xenoliths with eclogite and peridotite leads one to suspect that the granulite xenoliths have been brought up from the lower crust. On the basis of the sizes of xenoliths from the Moses Rock Pipe, McGetchin and Silver (1972) constructed a crustal model in which a major part of the lower crust is composed of mafic granulite rocks.

One method of obtaining estimates of crustal composition is to compare seismological data with laboratory measurements of rock velocities. Because granulite-facies rocks may well be abundant in the lower crust, it is necessary to determine their velocities and elastic properties. Christensen (1969) reported compressional and shear wave velocities for granulite-facies rocks at hydrostatic pressures to 10 kb (the approximate pressure at the continental crust–mantle boundary; see also Goodacre, 1972, and Ramananantoandro and Manghnani, 1972). We report here the measurement of compressional and shear wave velocities and the elastic constants of granulite-facies rocks of considerably varying chemical composition and mineralogy to hydrostatic pressures of 10 kb. We have

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found that seismic velocities and the related elastic constants of granulite rocks vary systematically with mineralogy. The data are used to estimate lower crustal mineral compositions in selected regions where detailed crustal seismic information is available.

NOTATION

V_p, compressional wave velocity, km/sec^{-1}
V_s, shear wave velocity, km/sec^{-1}
ρ, bulk density, g/cc
σ, Poisson's ratio
B, compressibility, Mb^{-1}
λ, Lamés' constant, Mb
μ, shear modulus, Mb
E, Young's modulus, Mb
K, bulk modulus, Mb
ϕ, seismic parameter (km/sec^{-1})^2

SAMPLE DESCRIPTIONS

Beginning with the early work of Eskola (1920), metamorphic rocks have been classified into various facies based on assemblages of mineral phases that form in various temperature-pressure regimes. The granulite facies was originally defined to include regionally metamorphosed rocks in which only anhydrous minerals are stable (Eskola, 1939). Later classifications have both subdivided the granulite-facies rocks into subfacies and expanded upon the original definition to include rocks transitional between the amphibolite and granulite facies. Although more comprehensive subdivisions have been proposed for the granulite facies (for example, de Waard, 1965a, 1965b), the twofold subdivision of Turner and Verhoogen (1960) is particularly appropriate for a discussion of the elasticity of granulite rocks and will be used throughout this paper. According to this classification, granulite facies are subdivided into the hornblende-granulite subfacies and the pyroxene-granulite subfacies. Rocks from the latter subfacies are formed at higher temperatures for given water pressures and lack the hydrous minerals hornblende and biotite.

Ten granulite samples that show a wide range in composition and density were selected for this study. Modal analyses obtained by point counting two or three thin sections from each sample are given in Table 1, in which the samples are arranged in order of increasing density, the more granitic and syenitic granulite rocks being near the top and the more mafic at the bottom. Five of the samples contain hornblende and (or) biotite and thus are classified within the hornblende-granulite subfacies.

Sample 1 is representative of granulite described in detail by Smith (1969) as hypersthene-quartz-andesine gneiss from the southern block of the New Jersey highlands. Although the sample selected for our study is compositionally layered, no preferred mineral orientation is apparent either in hand sample or in thin section.

Sample 2, from Tichborne, Ontario, is gray gneiss of the Grenville province and has been described in detail by Giovanella (1965). The rock contains primarily feldspar and quartz and exhibits a strong lineation in hand sample. The lineation is due to linear concentrations of pyroxene that lack preferred orientation (Giovanella, 1965).

The samples of California granulite (samples 3, 6, 8) that form part of the core of the Santa Lucia Range were collected along the Pacific coast approximately 25 km southeast of Point Sur. Although there is considerable variation in composition among the three rocks, it is apparent from their mineralogy (Table 1) that they were formed under conditions of hornblende-granulite–subfacies metamorphism. The mafic minerals within the samples show distinct preferred orientation, even though mineral segregation is lacking. The petrography and chemistry of these rocks have been described in detail by Compton (1960).

The samples of New York granulite collected near Saranac Lake (samples 4, 5, 7) have been described as charnockitic gneiss by Buddington (1952) and as quartz syenite gneiss by Davis (1971). Compositional banding and preferred mineral orientation are weakly developed in the specimens we studied from this area. Sample 7 is texturally similar to samples 4 and 5 but lacks quartz and contains more pyroxene (Table 1).

TABLE 1. MODAL ANALYSES (PERCENTAGES BY VOLUME)

Sample no. and locality	Qtz	Mi	Pl	Ho	Py	Others
1, New Jersey highlands	24	1	67	..	6	2 ma
2, Tichborne, Ontario	21	7	63	..	4	3 ma, 1 bi, 1 ga
3, Santa Lucia Mtns., California	7	..	74	8	8	2 bi, 1 ma
4, Saranac Lake, New York	2	43*	36	..	11	1 ga, 3 my, 4 ma
5, Saranac Lake, New York	3	48*	30	4	9	5 my, 1 ma
6, Santa Lucia Mtns., California	2	..	53	22	18	3 bi, 2 ma
7, Adirondack Mtns., New York	..	30*	32	..	38	..
8, Santa Lucia Mtns., California	6	..	32	54	4	3 ga, 1 ma
9, Wind River Mtns., Wyoming	..	..	36	42	22	..
10, Valle d'Ossola, Italy	..	1	60	..	26	9 ga, 4 ma

Note: bi = biotite, ga = garnet, ho = hornblende, ma = magnetite, mi = microcline, my = myrmekite, pl = plagioclase, py = pyroxene, qtz = quartz.

* Perthitic microcline.

Samples 9 and 10 are mafic representatives of the granulite facies. Sample 9, described by Barrus (1970), contains abundant hornblende and pyroxene, placing it within the hornblende-granulite subfacies. A strong lineation of hornblende is evident in hand sample and thin section. Sample 10, described by Schmid (1967), is from the Ivrea-Verbano zone in the Italian Alps. The rock shows no obvious preferred mineral orientation or compositional layering. Pyroxene and garnet are abundant, producing the highest density of the rocks included in this study.

EXPERIMENTAL TECHNIQUE AND DATA

Three mutually perpendicular cores, 2.54 cm in diameter and 5 to 7 cm in length, were cut from each specimen. Bulk densities (Table 2) were calculated using the weights and dimensions of the cores. The cores were jacketed with copper foil, and transducers, electrodes, and rubber tubing were assembled on each end in a manner similar to the procedure described by Birch (1960).

Velocities were obtained from the travel times of elastic waves through samples of known length using the pulse transmission technique (Birch, 1960). Barium titanate and AC-cut quartz transducers of 2 MHz frequencies were used to generate and receive compressional and shear waves, respectively. The pressure-generating system consists of a two-stage intensifier using a low-viscosity oil for the pressure medium. Pressure was measured by observing the change in electrical resistance of a calibrated manganin coil located on the high-pressure side of the intensifier.

The velocities given in Table 2 are uncorrected for length changes resulting from compression at elevated pressures. For most rocks, this correction lowers velocity at 10 kb approximately 0.02 km/sec and is significant only in calculating elastic constants and pressure derivatives of velocity. The compressional and shear wave velocities are estimated to be accurate to 0.5 percent and 1 percent, respectively (Christensen and Shaw, 1970).

Ratios of V_p to V_s and the elastic constants of the granulite samples calculated from the relations between elastic constants, velocities, and density (Birch, 1961) are given in Table 3. The velocities and densities used for the calculations were corrected for compression using an iterative technique and the dynamically determined compressibilities.

SEISMIC VELOCITIES AND GRANULITE MINERALOGY

Birch (1961) has shown that, to a first approximation, compressional wave velocities are linearly related to density for rocks of constant mean atomic weight. On the basis of shear wave velocity measurements by Simmons (1964), Kanamori and Mizutani (1965), and Christensen (1966a, 1966b), Christensen (1968) demonstrated that a similar relationship exists between shear velocity and density. The mean atomic weight (m) of a rock is calculated from its chemical analysis with the relation $m = (\sum x_i/m_i)^{-1}$, where m_i and x_i are the mean atomic weight and proportion by weight of oxide i, respectively. Calculations by Birch (1961) have shown that most common rocks have mean atomic weights between 20 and 22 and that differences in mean atomic weights of rock are primarily related to iron content — higher iron content gives a higher mean atomic weight.

In granulite, iron is often located in the crystal lattices of pyroxene, amphibole, garnet, biotite, and magnetite. An increase in the percentages of these minerals at the expense of feldspar and quartz will thus increase mean atomic weight. For the granulite samples included in this study, the percentages of iron-bearing minerals show a tendency to increase with increasing density (Tables 1, 2); therefore, mean atomic weight increases with increasing density, and velocities should not follow lines of constant mean atomic weight. In Figure 1, granulite velocities at 6 kb and Poisson's ratios calculated from the velocities are plotted against bulk density. Also shown are mean atomic weight lines $m = 21$ determined for compressional wave velocities by Birch (1961) and shear wave velocities by Christensen (1968). Although the velocity-density data do not follow lines of constant mean atomic weight, a linear relation between V_p and ρ is apparent. The least-squares linear solution is given by

$$V_p = 0.31 + 2.27\rho,$$

with a correlation coefficient of 0.95. Compressional wave velocities for the higher density granulite rocks fall below the constant mean atomic weight line 21 (that is, toward lines of higher mean atomic weight), as predicted from their mineralogy. Shear velocities, however, do not show a linear relation between density and velocity; for granulite rocks with densities below approximately 2.85 g/cc, the shear velocities decrease with increasing density, and above 2.85 g/cc, the velocities increase with increasing density. Poisson's ratio first increases with increasing density and then decreases (Fig. 1), with the exception of sample 10.

The unusual relation between shear velocity and density is readily explained by the mineralogy of the granulite rocks. The increase in shear velocity with increasing density for granulite rocks with densities above 2.85 g/cc is due to increasing pyroxene, hornblende, and garnet content. These minerals have higher aggregate velocities than feldspars and quartz (Table 4). The relatively low shear velocity and high Poisson's ratio for sample 10 are related to the high feldspar content of this rock (Tables 1, 4). For the lower density samples, there is a decrease in quartz content with increasing density. Compared to many other common silicates, quartz has a relatively low compressional wave velocity and a high shear wave velocity (a low Poisson's ratio). Thus, decreasing quartz content will increase compressional wave velocity and *decrease* shear wave velocity, as observed

TABLE 2. COMPRESSIONAL AND SHEAR WAVE VELOCITIES (KM/SEC)

Sample no. and locality	Bulk density (g/cm³)	p = 0.4 kb		p = 1.0 kb		p = 2.0 kb		p = 4.0 kb		p = 6.0 kb		p = 8.0 kb		p = 10.0 kb	
		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
1, New Jersey Highlands	2.671	6.13	3.68	6.25	3.72	6.350	3.762	6.428	3.790	6.482	3.805	6.518	3.814	6.542	3.820
	2.693	6.32	3.55	6.43	3.59	6.510	3.620	6.595	3.642	6.640	3.650	6.669	3.653	6.690	3.655
	2.678	6.32	3.67	6.40	3.69	6.469	3.721	6.548	3.744	6.595	3.758	6.628	3.767	6.650	3.773
Mean	2.681	6.26	3.63	6.36	3.67	6.443	3.701	6.523	3.725	6.572	3.738	6.605	3.745	6.627	3.749
2, Tichborne, Ontario	2.715	5.99	3.29	6.05	3.34	6.162	3.414	6.308	3.526	6.406	3.587	6.464	3.613	6.483	3.620
	2.709	5.99	3.20	6.09	3.26	6.195	3.341	6.339	3.466	6.432	3.539	6.482	3.575	6.507	3.586
	2.713	5.94	3.25	6.03	3.33	6.140	3.417	6.292	3.538	6.390	3.603	6.439	3.635	6.460	3.644
Mean	2.712	5.97	3.25	6.06	3.31	6.166	3.391	6.313	3.510	6.409	3.576	6.462	3.608	6.483	3.617
3, Santa Lucia Mtns., California	2.729	6.28	3.24	6.45	3.29	6.541	3.324	6.648	3.348	6.715	3.362	6.772	3.373	6.795	3.380
	2.726	6.41	3.46	6.47	3.50	6.515	3.555	6.572	3.599	6.615	3.630	6.655	3.655	6.690	3.679
	2.729	6.48	3.59	6.55	3.64	6.632	3.683	6.700	3.717	6.738	3.749	6.772	3.765	6.800	3.770
Mean	2.728	6.39	3.43	6.49	3.48	6.563	3.521	6.640	3.555	6.689	3.580	6.733	3.598	6.762	3.610
4, Saranac Lake, New York	2.846	6.17	3.22	6.43	3.31	6.553	3.350	6.635	3.382	6.672	3.396	6.705	3.405	6.731	3.410
	2.771	5.99	3.24	6.32	3.32	6.500	3.375	6.637	3.415	6.698	3.438	6.738	3.458	6.771	3.472
	2.873	6.13	3.25	6.43	3.37	6.573	3.415	6.695	3.450	6.752	3.468	6.784	3.481	6.800	3.490
Mean	2.830	6.09	3.24	6.40	3.33	6.542	3.380	6.656	3.416	6.707	3.434	6.742	3.448	6.767	3.457
5, Saranac Lake, New York	2.806	6.26	3.38	6.46	3.43	6.575	3.485	6.687	3.539	6.754	3.556	6.800	3.560	6.830	3.568
	2.866	5.97	3.29	6.26	3.37	6.410	3.417	6.531	3.452	6.580	3.462	6.603	3.468	6.615	3.470
	2.862	6.24	3.26	6.47	3.31	6.616	3.378	6.732	3.453	6.775	3.486	6.807	3.497	6.833	3.508
Mean	2.845	6.16	3.31	6.40	3.37	6.534	3.427	6.650	3.481	6.703	3.501	6.737	3.508	6.759	3.515
6, Santa Lucia Mtns., California	2.892	6.79	3.66	6.88	3.70	6.951	3.736	7.030	3.769	7.085	3.792	7.120	3.811	7.149	3.823
	2.916	6.32	3.58	6.60	3.63	6.725	3.659	6.813	3.675	6.855	3.682	6.890	3.686	6.920	3.688
	2.890	6.67	3.58	6.75	3.61	6.820	3.642	6.883	3.672	6.920	3.690	6.949	3.700	6.975	3.709
Mean	2.899	6.60	3.61	6.75	3.65	6.832	3.679	6.909	3.705	6.953	3.721	6.986	3.732	7.015	3.740
7, Adirondack Mtns., New York	2.963	6.71	3.71	6.78	3.74	6.858	3.778	6.943	3.808	6.983	3.828	7.015	3.845	7.042	3.855
	2.905	6.75	3.70	6.82	3.73	6.888	3.762	6.970	3.790	7.012	3.805	7.047	3.818	7.077	3.823
	2.916	6.80	3.63	6.86	3.71	6.935	3.750	7.003	3.785	7.040	3.804	7.071	3.816	7.096	3.821
Mean	2.928	6.75	3.68	6.82	3.73	6.894	3.763	6.972	3.794	7.012	3.812	7.044	3.826	7.072	3.833
8, Santa Lucia Mtns., California	2.995	6.11	3.50	6.38	3.60	6.600	3.679	6.779	3.751	6.865	3.785	6.931	3.804	6.980	3.812
	2.993	6.41	3.59	6.71	3.71	6.940	3.810	7.125	3.896	7.221	3.934	7.300	3.953	7.379	3.960
	2.960	6.25	3.49	6.44	3.60	6.650	3.667	6.818	3.724	6.897	3.744	6.950	3.753	6.987	3.759
Mean	2.983	6.26	3.53	6.51	3.63	6.730	3.719	6.907	3.790	6.994	3.821	7.060	3.837	7.115	3.844
9, Wind River Mtns., Wyoming	3.048	6.83	4.07	7.07	4.11	7.181	4.160	7.256	4.212	7.310	4.248	7.354	4.272	7.396	4.288
	3.048	7.33	4.03	7.42	4.09	7.499	4.141	7.573	4.197	7.616	4.230	7.642	4.252	7.660	4.263
	3.010	6.65	3.62	6.84	3.72	7.021	3.836	7.119	3.945	7.175	3.985	7.220	4.005	7.254	4.018
Mean	3.035	6.94	3.91	7.11	3.97	7.234	4.046	7.316	4.118	7.367	4.154	7.405	4.176	7.434	4.190
10, Valle d'Ossola, Italy	3.055	6.10	3.47	6.79	3.74	7.098	3.851	7.306	3.954	7.430	4.000	7.502	4.027	7.520	4.054
	3.132	6.35	3.54	6.78	3.75	7.143	3.904	7.400	4.008	7.486	4.041	7.530	4.070	7.555	4.097
	3.067	6.08	3.43	6.50	3.63	6.924	3.775	7.174	3.877	7.284	3.906	7.338	3.903	7.377	3.956
Mean	3.085	6.18	3.48	6.68	3.71	7.055	3.843	7.293	3.946	7.400	3.982	7.457	4.000	7.484	4.036

for the granulite samples plotted in Figure 1. This observation may prove to have important implications in future interpretations of crustal low-velocity zones. Several seismic investigations (for example, Landisman and others, 1971; Mueller and Landisman, 1966) have cited evidence for the presence of compressional wave low-velocity zones in the continental crust. It is possible that decreasing quartz content with depth in crustal rocks could cause a velocity inversion of quite a different sort: one for shear waves but not for compressional waves. At present, however, because very little information is available on shear wave velocities in the continental crust, there is no evidence either supporting or disproving the existence of crustal shear wave low-velocity zones.

The mineralogies of the granulite rocks are related in a complex manner to the velocities. To a first approximation, compressional wave velocities in granulite rocks increase systematically with increasing pyroxene, amphibole, and garnet content. Figure 2 shows modal percentages of these minerals (Table 1) with compressional wave velocities between 4 and 10 kb. The data in Figure 2 also emphasize the importance of pyroxene versus amphibole content (that is, subfacies mineralogy) on compressional wave velocities. Because pyroxenes have significantly higher velocities than amphiboles (Table 4), granulite rocks of the pyroxene-granulite subfacies have higher velocities than hornblende-granulite–subfacies rocks of roughly equivalent percentages of mafic minerals. It follows that in hornblende-granulite–subfacies rocks, the amount of hornblende relative to pyroxene will significantly influence velocities. For example, samples 8 and 9 have approximately equivalent percentages of total amphibole plus pyroxene (Table 1; Fig. 2); however, due primarily to a greater percentage of pyroxene, sample 9 has higher velocities. Additional comparisons of samples 3 and 4 and samples 6 and 7 (Fig. 2) also illustrate this influence of metamorphic grade on velocities.

A more detailed examination of the influence of mineralogy on elastic properties may be made with the use of triangular velocity-mineralogy diagrams similar to those used by Christensen (1966b) for ultramafic mineral assemblages. Velocities of the individual mineral components for these diagrams can be obtained from theoretical Voigt-Reuss-Hill averages of single-crystal elastic constants (Table 4). It should be emphasized that the velocities given in Table 4 are for atmospheric pressure determinations, and there is uncertainty about the correct technique to be used to calculate aggregate velocities from single-crystal data (Birch, 1972; Thomsen, 1972). Nevertheless, calculations of rock velocities from Voigt-Reuss-Hill averages tend to agree quite well with measured velocities at pressures above 1 to 2 kb when the effects of grain boundary cracks on velocity are negligible (Christensen, 1965, 1966a).

In the following discussion, the emphasis will be on changes in velocity that accompany changes in mineralogy, rather than on the values of the aggregate velocities themselves. In this way, the averaging technique used to obtain single-crystal aggregate velocities has less importance, and the effects of pressure on mineral velocities, which are unknown for many of the minerals listed in Table 4, can, to a first approximation, be neglected. Aggregate velocities and Poisson's ratios have been calculated for four major three-component mineral assemblages typical of granulite-facies rocks: bronzite + quartz + plagioclase (An_{29}), bronzite + perthite + plagioclase (An_{29}), bronzite + hornblende + plagioclase (An_{56}), and bronzite + garnet + plagioclase

TABLE 3. ELASTIC CONSTANTS CALCULATED FROM V_p, V_s, AND ρ

Pressure (kb)	V_p/V_s	σ	ϕ (km/sec)^2	K (Mb)	β (Mb^{-1})	μ (Mb)	E (Mb)	λ (Mb)
				Sample 1				
0.4	1.72	0.25	21.6	0.58	1.73	0.35	0.88	0.34
2.0	1.74	0.25	23.2	0.62	1.60	0.37	0.92	0.38
6.0	1.76	0.26	24.4	0.66	1.51	0.38	0.95	0.41
10.0	1.77	0.26	24.9	0.68	1.47	0.38	0.96	0.42
				Sample 2				
0.4	1.84	0.29	21.6	0.59	1.70	0.29	0.74	0.40
2.0	1.82	0.28	22.6	0.62	1.62	0.31	0.80	0.41
6.0	1.79	0.27	23.9	0.65	1.53	0.35	0.89	0.42
10.0	1.79	0.27	24.3	0.67	1.49	0.36	0.91	0.43
				Sample 3				
0.4	1.86	0.30	25.1	0.69	1.46	0.32	0.83	0.47
2.0	1.86	0.30	26.5	0.72	1.38	0.34	0.87	0.50
6.0	1.87	0.30	27.5	0.76	1.32	0.35	0.91	0.52
10.0	1.87	0.30	28.1	0.78	1.29	0.36	0.93	0.54
				Sample 4				
0.4	1.88	0.30	23.1	0.65	1.53	0.30	0.77	0.46
2.0	1.94	0.32	27.5	0.78	1.28	0.32	0.85	0.57
6.0	1.95	0.32	29.1	0.82	1.20	0.33	0.88	0.61
10.0	1.96	0.32	29.6	0.85	1.18	0.34	0.90	0.62
				Sample 5				
0.4	1.86	0.30	23.3	0.66	1.51	0.31	0.81	0.46
2.0	1.90	0.31	27.0	0.80	1.30	0.33	0.88	0.55
6.0	1.91	0.31	28.4	0.82	1.23	0.35	0.92	0.58
10.0	1.92	0.31	29.0	0.83	1.20	0.35	0.92	0.60
				Sample 6				
0.4	1.83	0.29	26.2	0.76	1.32	0.38	0.97	0.51
2.0	1.86	0.30	28.6	0.83	1.21	0.39	1.01	0.57
6.0	1.87	0.30	29.8	0.87	1.15	0.40	1.04	0.60
10.0	1.88	0.30	30.3	0.89	1.13	0.41	1.06	0.62
				Sample 7				
0.4	1.84	0.29	27.5	0.81	1.24	0.40	1.02	0.54
2.0	1.83	0.29	28.6	0.84	1.19	0.41	1.07	0.56
6.0	1.84	0.29	29.7	0.87	1.14	0.43	1.10	0.59
10.0	1.85	0.29	30.2	0.89	1.12	0.43	1.12	0.61
				Sample 8				
0.4	1.77	0.27	22.5	0.67	1.49	0.37	0.94	0.42
2.0	1.81	0.28	26.8	0.80	1.25	0.41	1.06	0.52
6.0	1.83	0.29	29.3	0.88	1.14	0.43	1.12	0.59
10.0	1.85	0.29	30.7	0.93	1.08	0.44	1.14	0.63
				Sample 9				
0.4	1.77	0.27	27.8	0.84	1.19	0.46	1.18	0.53
2.0	1.78	0.27	30.5	0.93	1.08	0.50	1.27	0.60
6.0	1.77	0.27	31.1	0.95	1.05	0.53	1.33	0.60
10.0	1.77	0.27	31.6	0.97	1.03	0.53	1.36	0.61
				Sample 10				
0.4	1.78	0.27	22.0	0.68	1.47	0.37	0.95	0.43
2.0	1.84	0.29	30.0	0.93	1.08	0.46	1.18	0.62
6.0	1.86	0.30	33.5	1.04	0.96	0.49	1.27	0.71
10.0	1.85	0.29	34.1	1.06	0.94	0.50	1.31	0.73

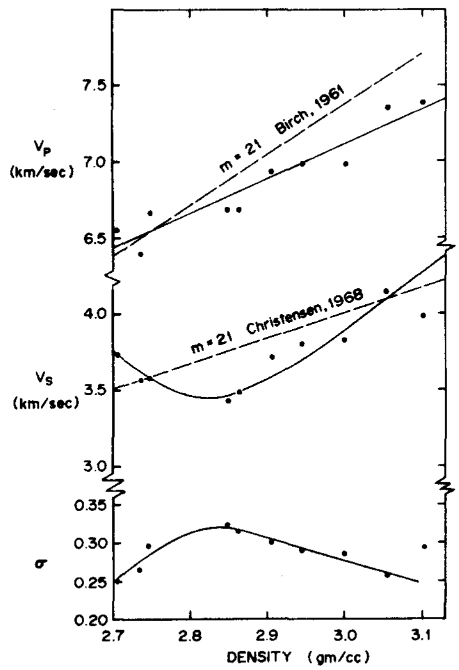

Figure 1. Compressional wave velocity, shear wave velocity, and Poisson's ratio at 6 kb versus density for granulite-facies rocks.

TABLE 4. AGGREGATE VELOCITIES AT ATMOSPHERIC PRESSURE FOR SELECTED MINERALS COMMON IN GRANULITE

Mineral	Composition	Density (g/cc)	V_p (km/s)	V_s (km/s)	Reference
Microcline		2.56	6.01	3.34	Alexandrov and Ryzhova, 1962
Perthite	79% Or, 19% Ab, 2% An	2.56	5.91	3.25	Ryzhova and Alexandrov, 1965
Plagioclase	9% An	2.61	6.07	3.34	Ryzhova, 1964
Plagioclase	24% An	2.64	6.22	3.40	Ryzhova, 1964
Plagioclase	29% An	2.64	6.35	3.44	Ryzhova, 1964
Quartz		2.65	6.05	4.09	McSkimin and others, 1965
Plagioclase	53% An	2.68	6.57	3.53	Ryzhova, 1964
Plagioclase	56% An	2.69	6.62	3.57	Ryzhova, 1964
Biotite		3.05	5.26	2.87	Alexandrov and Ryzhova, 1961a
Hornblende		3.15	7.04	3.81	Alexandrov and Ryzhova, 1961b
Diopside		3.31	7.70	4.38	Alexandrov and others, 1964
Bronzite	85% En	3.34	7.84	4.75	Kumazawa, 1969
Garnet	Almandite-pyrope	4.16	8.53	4.76	Soga, 1967
Garnet	Almandite	4.18	8.52	4.77	Verma, 1960
Magnetite		5.18	7.40	4.20	Doraiswami, 1947

(An_{53}). The results of these calculations are shown in Figures 3 and 4.

Samples 1, 2, and 3 are plotted in Figure 3(a). The diagrams of Figure 3(a) predict that these rocks should have nearly equal shear velocities, whereas compressional wave velocities of sample 3 should be significantly higher than those of samples 1 and 2. This agrees well with the measured velocities (Table 2). More importantly, Figure 3(a) illustrates the effect of quartz on the aggregate properties of granulite-facies rocks. Along the line from point A to point B on the diagrams, V_p increases, but V_s decreases. This direction corresponds to the direction of the maximum decrease in Poisson's ratio. Note that this direction does not coincide with the direction of maximum decrease of the percentage of quartz, because Poisson's ratio is controlled by three mineral components, not quartz alone.

The assemblage bronzite + perthite + An_{29} (Fig. 3) differs from the previous assemblage by the substitution of perthite for quartz. Granulite samples of this mineralogy (4, 5, 7) are plotted in Figure 3(b). It is clear that the differences between V_p and V_s between sample 7 and samples 4 and 5 are primarily due to differences in pyroxene content, because the velocity contours are subparallel to lines of constant pyroxene percentage. Thus, a small change in the percentage of pyroxene will greatly influence the aggregate velocity. Figure 3(b) also shows that the velocity contours for V_p and V_s are nearly parallel to each other, in marked contrast to the velocity contours for Figure 3(a). This difference again points to the unusual elastic behavior of quartz in influencing overall elastic properties of granulite-facies rocks.

Samples 6, 8, and 9 are plotted in Figure 4(a), the bronzite + hornblende + An_{56} assemblage. This assemblage illustrates the interplay of pyroxene and hornblende in determining the elastic properties of granulite-facies rocks. Consider any line of constant pyroxene + hornblende. As this line is followed in the direction of increasing pyroxene [for example, A to B, in Fig. 4(a)] compressional wave velocities increase. Thus the diagram illustrates the effect of increasing pyroxene at the expense of hornblende on compressional wave velocities, as discussed earlier in conjunction with Figure 2. One should keep in mind, however, that recent measurements in our laboratory of velocities in hornblendite indicate that the hornblende shear velocity in Table 4 and Figure 4(a) may be low by as much as 0.3 km/sec.

Figure 4(b) illustrates the bronzite + garnet + An_{53} assemblage appropriate to sample 10. The important fact here is that V_p is relatively insensitive to the percentage of bronzite (note that the velocity contours are perpendicular to the lines of equal percentage of bronzite). The compressional wave velocity is changed most readily by changing the ratio of garnet to plagioclase.

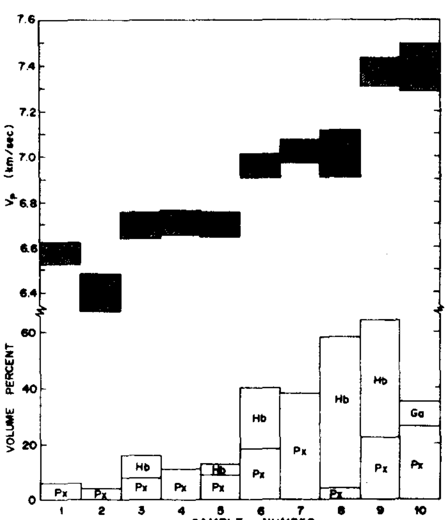

Figure 2. Percent pyroxene (Px), hornblende (Hb), and garnet (Ga) for granulite-facies rocks and ranges of compressional wave velocities between 4 and 10 kb.

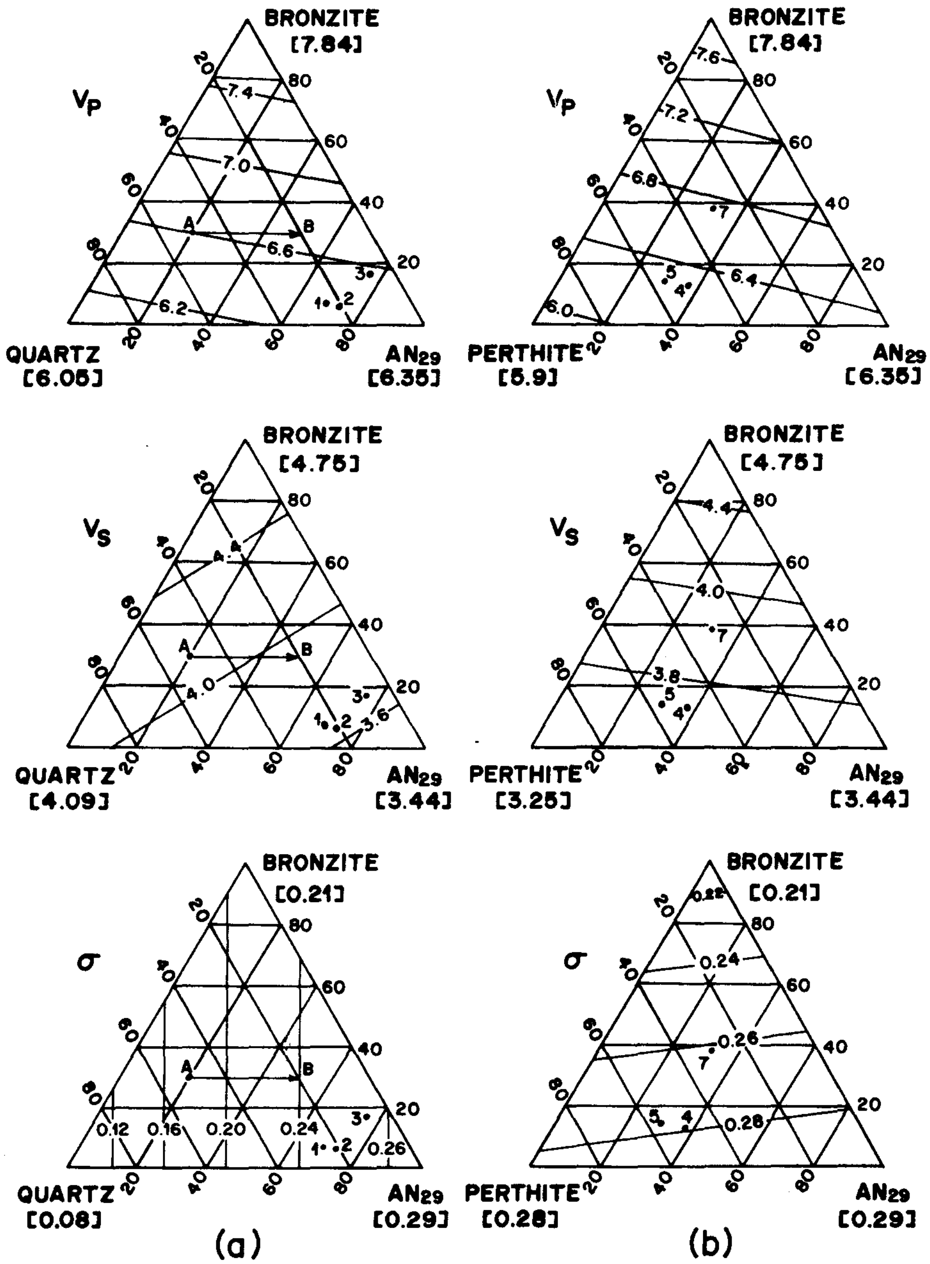

Figure 3. Aggregate values of compressional and shear wave velocity and Poisson's ratio for assemblages (a) bronzite + quartz + An_{29} and (b) bronzite + perthite + An_{29}.

COMPOSITION OF THE LOWER CONTINENTAL CRUST

Estimates of lower crustal composition based on field relations have been, to some extent, substantiated by experimental studies of high-temperature and high-pressure mineralogic assemblages. Kennedy's (1959) preliminary experiments on the gabbro-eclogite phase transformation for basaltic compositions showed that mineral assemblages characteristic of granulite-facies metamorphism (pyroxene + plagioclase ± garnet ± quartz) are stable up to the eclogite stability field and, on the basis of extrapolations, suggested that these assemblages should be stable at the pressure-temperature conditions of the lower continental crust. Subsequent experiments conducted by Yoder and Tilley (1962), Cohen and others (1967), Ito and Kennedy (1970, 1971), and Kennedy and Ito (1972) provided data in support of Kennedy (1959). Ringwood and Green's (1964) preliminary results, however, indicated that eclogite mineral assemblages may be the stable phases for basaltic compositions at lower crustal pressure-temperature conditions. In more detailed work that followed (Ringwood and Green, 1966a, 1966b; Green and Ringwood, 1967, 1972), extrapolations of extremely high pressure gabbro-granulite-eclogite stability data to the lower pressures and temperatures expected for the continental crust further suggested that under anhydrous conditions, eclogite and possibly garnet granulite are the stable phases of basaltic composition in the crust.

Fewer data are available on the stability of high-pressure and high-temperature mineral assemblages for intermediate and acidic compositions. Green and Lambert (1965), however, studying crystallization of various mineral phases in a starting material of granitic composition, found that granulite-facies mineral assemblages (quartz + plagioclase + alkali feldspar + pyroxene ± garnet) are stable at the pressure-temperature conditions of the lower crust. These authors thus suggested that these laboratory-generated assemblages have natural analogs in many acid granulite and charnockite terranes. In a more recent study of gabbroic anorthosite and diorite compositions, T. H. Green (1970) also found granulite mineralogies of these compositions to be stable assemblages under lower crustal conditions. There are, therefore, data from experimental studies indicating that granulite-facies assemblages of acidic and intermediate compositions may be important stable phases of the lower crust.

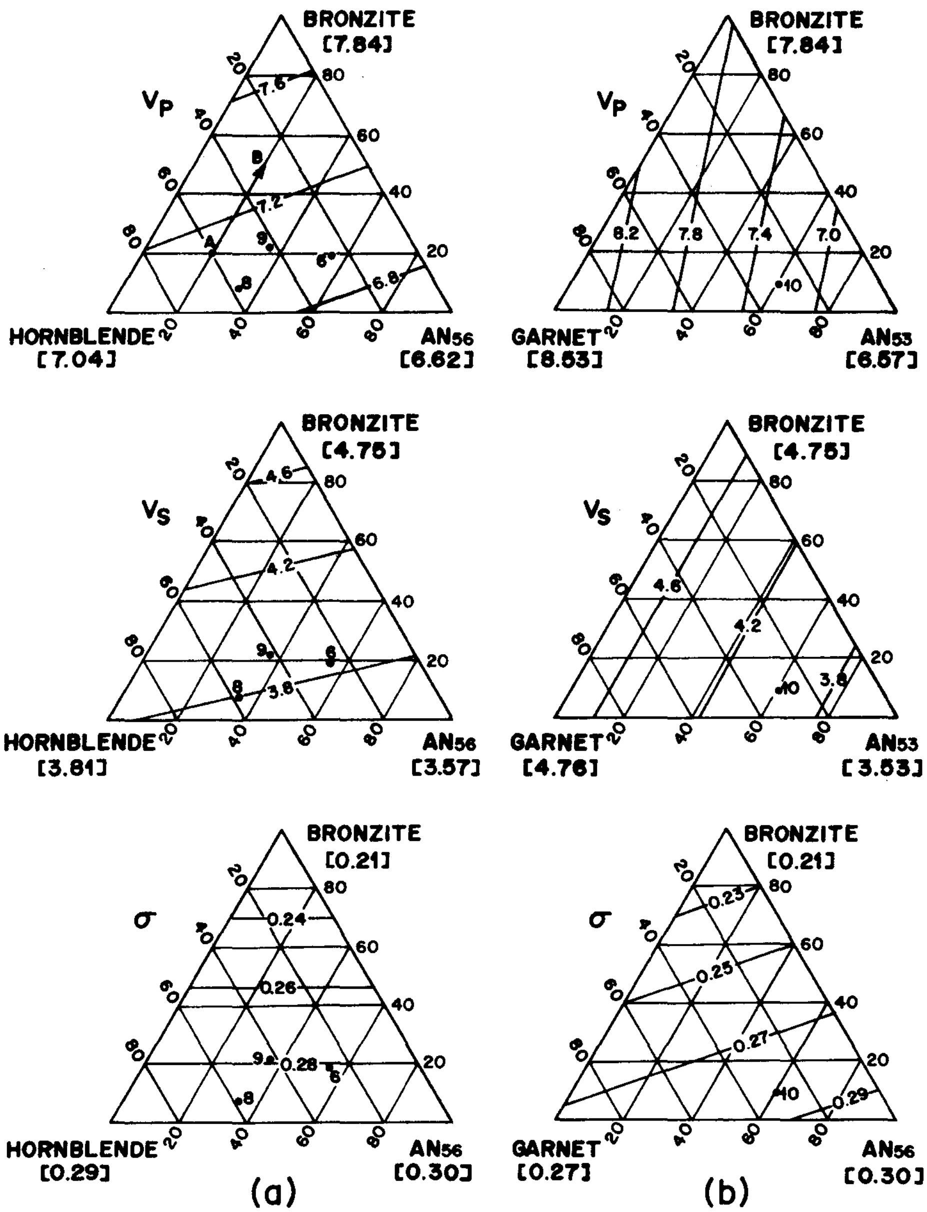

Figure 4. Aggregate values of compressional and shear wave velocity and Poisson's ratio for assemblages (a) bronzite + hornblende + An_{56} and (b) bronzite + garnet + An_{53}.

Variability in Lower Crustal Composition

Although experimental investigations on mineral stability fields at relatively high temperatures and pressures and estimates of pressure and temperature conditions within the crust suggest that rocks of the granulite facies may be ubiquitous constituents of the deep crust of the continents, any valid petrologic model for the lower crust based on granulite-facies mineralogy must satisfy comparisons of seismic data with observed velocities in granulite-facies rocks. The most widely accepted models of continental structure have been those determined through explosion seismology. Most crustal models are considered to be either two layered, the deeper layer separated from the upper layer by the Conrad discontinuity, or essentially one layered, with a shallow refractor at depths of a few kilometers extending to the Mohorovičić discontinuity. In some seismic refraction investigations, however, more than two layers have been reported (Hall and Hajnal, 1973; Mitchell and Landisman, 1971). These traditional pictures of the Earth's crust are undoubtedly oversimplified (James and Steinhart, 1966); we hope that future thorough examinations of velocity-depth relations will define continuous velocity profiles, which, in conjunction with laboratory measurement of rock velocities, will provide important information on changes in composition with depth.

A summary of more than 200 compressional wave velocities for crustal refractors at depths greater than 10 km in the lower continental crust is shown in Figure 5. A limitation of 10-km depth allows observations of continental crust below what would conventionally be called the Conrad discontinuity and precludes data from one-layer solutions. Figure 5 shows that lower crustal refractors exhibit an extremely wide range of compressional wave velocities, which suggests that the lower crust is quite variable in composition. Because of this variability, it should be emphasized that overall estimates of crustal composition are at present extremely tenuous (Poldervaart, 1955; Taylor, 1964; Taylor and White, 1965; Pakiser and Robinson, 1966; Wedepohl, 1969; Ronov and Yaroshevsky, 1969).

Also illustrated in Figure 5 is the range of compressional wave velocities between 4 and 10 kb for the 10 granulite-facies rocks we are concerned with here. The range of velocities for the granulite samples is clearly similar to the range of seismic velocities determined for the lower crust. As discussed in the preceding section, the variability of velocities for the samples is clearly related to their range of mineralogy and chemistry. Thus, if the lower crust is composed of granulite-facies mineral assemblages, a significant chemical and mineralogic inhomogeneity of the lower crust is implied.

Composition of the Crust Below the Canadian Shield

In the past few years, several seismic investigations have provided significant observations that allow more detailed analyses of crustal composition than were previously possible for classical two-layered crustal models. These observations included crustal shear velocities and hence Poisson's ratios, information on positive crustal velocity gradients, velocity reversals within the crust (Landisman and others, 1971), changes in Poisson's ratio with depth (Suzuki, 1965), and crustal anisotropy (Dorman, 1972). To show how some of these can be used to obtain a general picture of lower crustal composition, seismic observations for one particular region, the Canadian Shield, will be discussed.

Seismic refraction studies in Ontario and Manitoba (south and southwest of Hudson Bay) summarized by Hall and Hajnal (1973) provide excellent data for a comparison of refraction results with laboratory data. This region has been chosen because both compressional and shear wave velocities are reported, the stated accuracy of the measurements is high (most velocities are reported accurate to ±0.05 km/sec), and the region has been covered both extensively and in detail (84 deep seismic recordings). The crustal models determined for this region are summarized in Figure 6 (see Hall and Hajnal, 1973, for further details of these models). Figure 6(a) is determined from profiles straddling the boundary between the Churchill geologic province and the Superior geologic province and represents the crustal structure of the Churchill province. The west Ontario and east Manitoba models [Fig. 6(b), (c)] are for a region farther to the south and thus represent the crustal structure of the Superior province.

Refracted velocities for crust beneath the Conrad discontinuity [termed the Riel discontinuity by Hall and Hajnal (1973)] in these models are 6.95, 6.85, and 6.81 km/sec, and the eastern Manitoba section shows an additonal sub-Conrad refractor of 7.1 km/sec. Clearly these velocities are within the range of compressional wave velocities measured for granulite-facies rocks in this study. Knowledge of compressional wave velocity of the lower crust, however, does not provide adequate information to determine lower crustal composition; inspection of Figures 3 and 4 shows that a given V_p can be indicative of any number of mineral assemblages. If V_s is known, Poisson's ratio, a parameter

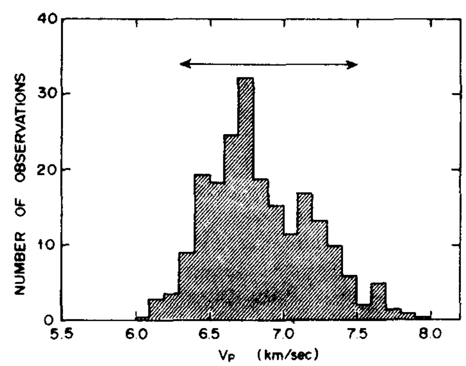

Figure 5. Histogram of compressional wave velocities for lower crust at depths greater than 10 km. Arrow indicates range of compressional wave velocities between 4 and 10 kb reported for granulite-facies rocks.

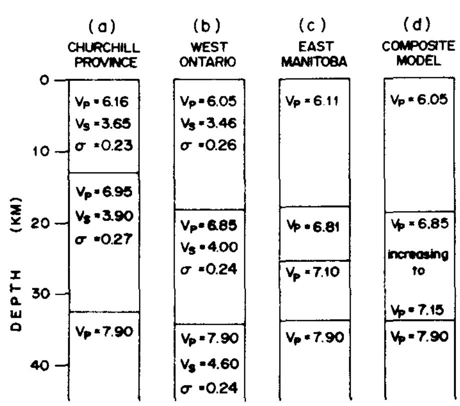

Figure 6. Velocity models for Churchill province, west Ontario, and east Manitoba, and composite model for Canadian Shield (after Hall and Hajnal, 1973).

thought to be insensitive to pressure and temperature (Crosson and Christensen, 1967; Fagerne and Kanestrøm, 1973) can be calculated and used in conjunction with V_p as a constraint on crustal composition. Superposition of the triangular diagrams for V_p and σ (Figs. 3, 4) produce intersections between V_p contours and σ contours that represent an estimate of composition for specific values of V_p and σ. Thus, if these two parameters are known for the lower crust of a region and granulite-facies stability is assumed, it may be possible to estimate lower crustal composition. Because the triangular diagrams (Figs. 3, 4) were calculated from atmospheric pressure values of elastic constants of the component minerals, a correction must be made for pressure. The average disagreement between the predicted velocities and those measured at 6 kb for the granulite samples is 0.2 km/sec; therefore, each velocity contour in Figures 3 and 4 has been augmented by that amount. Employing the corrected diagram for the assemblage bronzite + quartz + An_{29} [Fig. 7 (a)], an approximate estimate of 50 percent An_{29}, 27 percent bronzite, and 23 percent quartz can be made for the mineralogy of the lower crust of west Ontario (V_p = 6.85 km/sec, σ = 0.24). Figure 7(a) also predicts a mineralogy of 63 percent An_{29}, 31 percent bronzite, and 6 percent quartz for the lower crust of the Churchill province section (V_p = 6.95 km/sec, σ = 0.26). An alternate possibility of 65 percent An_{29}, 30 percent bronzite, and 5 percent perthite is given for the Churchill province mineralogy [Fig. 7(b)]. Note that the two estimates for the Churchill province section differ only by the substitution of a small percentage of perthite for quartz.

The two estimates for one region indicate the nonuniqueness of this approach. If more than the four mineral assemblages presented here had been examined, more estimates for one region may have been possible. It should be stressed that the variation of temperature with depth was not considered, because the change of V_p with temperature for many of the minerals used is not adequately known. The correction for pressure may also be in error. It is clear, however, that possible estimates of lower crustal composition cannot be made by use of compressional wave velocities alone. Although V_p measurements for the lower crust of the two regions discussed above are nearly equivalent, knowledge of Poisson's ratio in each case allows calculation of different compositions.

Hall and Hajnal (1973), in developing a composite model for the Canadian Shield, found evidence for a positive velocity gradient in the lower crust:

$$V_p = 6.70 \text{ km/sec} + 0.02\, z,$$

where z is the depth in kilometers. Thus, the refracted velocity at the Conrad discontinuity of 6.85 km/sec leads to a velocity of 7.15 km/sec at the base of the crust, a change of 0.3 km/sec. A similar gradient was observed in the Grenville province by Berry and Fuchs (1973). It is interesting that, for the rocks examined in this study, the average change of V_p over an equivalent pressure range of 6 to 10 kb is only 0.1 km/sec. This is significantly less than the change observed in the Canadian Shield and would be diminished further if the effect of temperature increases expected in the lower crust (Lachenbruch, 1970) were considered. Thus, the only way to explain this velocity gradient is by change of mineralogy with increasing depth with or without a change in chemistry. This suggested change of mineralogy with depth is expressed in the east Manitoba section by the sub-Conrad refractor of 7.10 km/sec. Goodacre's (1972) analysis of refraction data for Canada also implied a change of composition with depth. Other regions in which evidence for velocity gradients exist are Missouri (Stewart, 1968), Oklahoma (Mitchell and Landisman, 1971), and the western United States (Prodehl, 1970), showing that positive velocity gradients are not unique to the Canadian Shield. Steinhart and Meyer (1961) emphasized that many time-distance curves from seismic experiments can also be interpreted as resulting from velocity gradients instead of layers of constant velocity. Thus, in addition to lateral variations of composition, there is considerable evidence to suggest that the lower continental crust is further complicated by changes in mineralogy with depth.

SUMMARY AND CONCLUSIONS

Velocities and elastic constants of granulite-facies rocks are related to the elastic properties of their constituent minerals. To a first approximation, velocities and Poisson's ratios of granulite rocks can be predicted from their mineralogy with simple three-component diagrams. The diagrams are particularly useful in understanding how variations in mineralogy affect seismic velocities. Because these diagrams show that a variety of mineral combinations can have equivalent compressional wave velocities, the interpretation of lower crustal seismic wave velocities in terms of granulite-facies mineralogy requires shear-velocities in addition to compressional wave velocities.

Our knowledge of the structure and composition of the lower continental crust is still incomplete. However, the wide range of seismic compressional wave velocities implies extreme variability in composition. Because experimental studies of mineral stabilities suggest that common igneous rocks are unstable throughout the lower continental crust, we must turn to metamorphic assemblages in estimating lower crustal mineralogy. As has been shown from the velocity measurements presented in this paper, the range of lower continental crustal velocities can readily be explained in terms of granulite-facies mineralogy.

It should be emphasized that seismic velocity measurements do not rule out the possibility of amphibolite-facies rocks as being significant or even dominant constituents of the lower continental crust. In addition to temperature considerations, the nature of regional metamorphism in the deep crust depends upon the relation of water pressure to load pressure (see Binns, 1969, for review); unfortunately, present estimates of the distribution of water in the lower crust are highly subjective. Compressional wave velocities at 6 kb for amphibolite-facies rocks reported by Christensen (1965) vary from 6.15 to 7.75 km/sec, which is similar to the variation observed for granulite-facies rocks. Shear wave velocities of amphibolite-facies rocks (Christensen, 1966a) are also comparable with granulite shear wave velocities.

Because of the variability of mineral composition and therefore chemical composition implied by lower crustal seismic velocities, any estimate of average lower crustal composition based on seismic velocities must await a much more thorough study of velocity distributions within the crust. It is highly probable that in some regions the lower crust consists of granulite-facies mineralogy of intermediate composition, whereas overall compositions in other regions might be much different. In addition to regions of relatively uniform lower crustal composition, there undoubtedly are areas in which there are significant vertical changes in composition with depth, as has been discussed for the Canadian Shield.

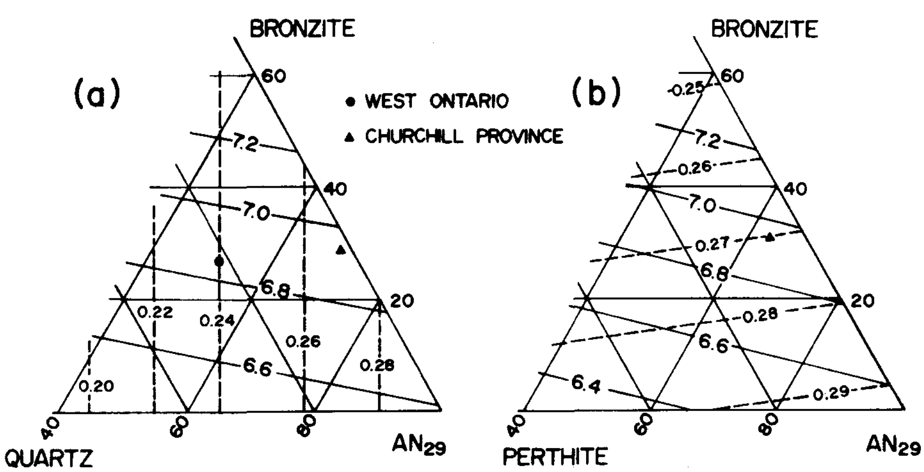

Figure 7. Compressional wave velocities and Poisson's ratios for assemblages (a) bronzite + quartz + An_{29} and (b) bronzite + perthite + An_{29}. Intersections of lines of constant V_p and σ (circle and small triangle) yield estimates of mineralogy for west Ontario and Churchill province velocity models.

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