ELASTIC WAVES VELOCITIES AND THE ANISOTROPY OF THE XENOLITHS FROM RACOŞ ALKALINE BASALTS

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The determination of velocities of the elastic waves in formations from the top of the terrestrial mantle can be done *in situ* by the study of the propagation velocities of Pn and Sn waves, and in the laboratory by using ultrasound to investigate the xenoliths from lavas that have crossed the lithospheric mantle. In this paper we present results of ultrasound investigation on peridotite xenoliths from Racoş and Bogata basalts and of some eclogite samples relatively similar compositional to the garnet pyroxenites found in Bogata. These two methods can also provide interesting information on the elastic anisotropy of rocks composing the upper part of the lithospheric mantle. We can model the average speed, the density and the elastic modulus of rocks, starting from their thermo-barometric conditions of equilibrium and from their modal composition.

Key words: xenolith, lithospheric mantle, anisotropy, velocities.

1. INTRODUCTION

The determination of the velocities of elastic waves through formations similar to the lithospheric mantle, performed on xenoliths embedded in the alkaline basalts from Racoş, arouses a great interest through the contribution such analyses can bring to elucidating the lithospheric mantle composition and structure of the Vrancea area and its vicinity.

The problem of the deep geological composition of the Eastern Carpathians bend area have been treated in recent years in terms of petrographic and geochemical properties by Vaselli *et al.* (1995), Szabo *et al.* (1995), Falus *et al.* (2000), Seghedi *et al.* (2004), Falus *et al.* (2008, 2011).

From the structural point of view several models have been created over the years, among which the most important being that of the delamination of lower crust and its descent into lithospheric mantle as a litospheric slab (Gîrbacea & Frisch, 1998) and the model of the unstable triple junction (Beşuţiu, 2006).

2. TYPES OF XENOLITHS COLLECTED FROM THE RACOŞ ALKALINE BASALTS

In terms of lithology most of xenoliths studied by Vaselli *et al.* (1995), Szabo *et al.* (2004) and Falus *et al.* (2008) are spinel lherzolite (Fig. 1). The olivine content of these samples ranges from 60 to 75% and the orthopyroxene content from 27 to 10%. Also some harzburgite with olivine content above 85% is found.

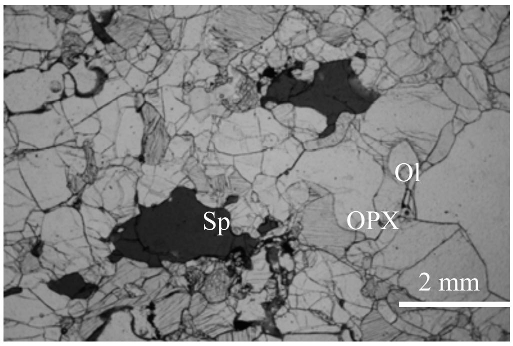

Fig. 1 – Peridotite xenolith with orthopyroxene and chrome-bearing spinel from Racoş.

An important feature of those xenoliths is their milonitic type structure, with crystals deformed and elongated, and extensive recrystallization phenomena (Falus, 2000, 2008). The anisotropy indicators for these xenoliths are represented by the crystals cleavage alignment for orthopyroxene and of compression structures for olivine.

In addition to peridotitic xenoliths, significant amounts of pyroxenites with garnet and spinels or with garnet, spinel and amphibole were also found (Fig. 2). The amphibole occur secondary by metasomatic transformation of the clinopyroxene.

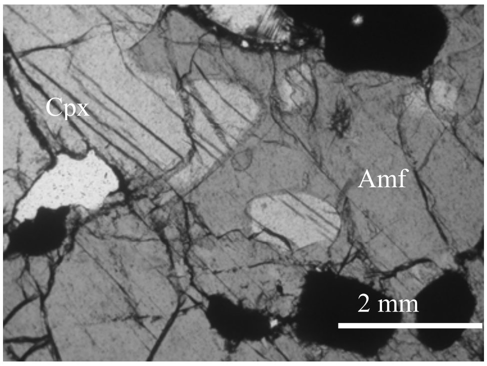

Fig. 2 – Secondary amphibole formed on clinopyroxene.

In some cases we can see the orientation of amphibole is similar to that of the pyroxene on which is formed, suggesting a sindeformational crystallization of the secondary mineral.

3. DETERMINATION OF THE ELASTIC WAVES VELOCITIES AND ANISOTROPY USING ULTRASOUNDS

To determine compressional and shear waves velocities and elastic anisotropy we used an ultrasound source (Fig. 3), measuring the propagation time of sound through a crystal or mineral association. For this purpose it is very important to know very exactly the outer dimensions of the sample. Rock samples were cut in cubes with a side length of 10 mm. The signal was successively applied on three orthogonal directions, determining the arrival times for this three directions, and for the frequencies of 5 MHz, 10 MHz and 20 MHz. Other frequencies are inadequate for this study, because the wavelength of oscillations is much larger than the sample size. Given the speed range for the studied type of rocks (about 8 km/s) the minimum size of a crystal which can be detected at a frequency of 5 MHz is about 1 mm, the average size of the olivine and pyroxene crystals encountered frequently in xenoliths from basalts.

We studied five samples of peridotite with modal compositions starting from 75% olivine and 15% orthopyroxene, six samples of pyroxenite with garnet and amphibole and ten samples of eclogitic type. Eclogitic samples were included in the studied material because among xenoliths of basalts from Racoş previously collected by Peter Luffi, several samples of eclogite with similar composition were found. Samples were chosen with different textural characters, from coarse grained porfiroclastic peridotite to the ultramilonitic and milonitic with phenomena of recrystallization and grain fine and very fine.

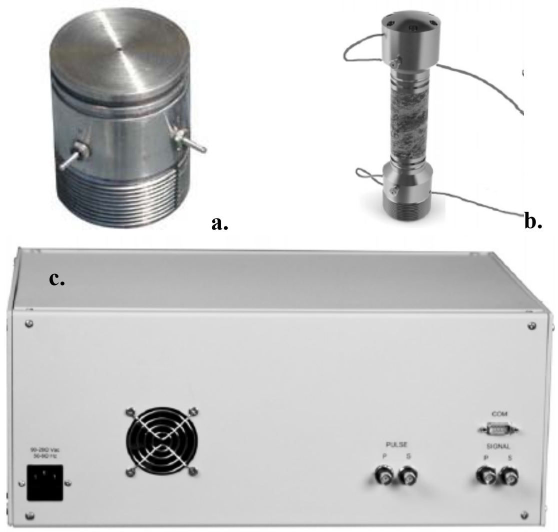

Fig. 3 – The device for elastic wave velocity measurement using ultrasound. a) planar sensor for measuring of velocities P and S; b) receiver-transmitter group assembled for testing of sediment samples; c) transmitter, receiver and the signal conditioning unit.

3.1. THE EQUIPMENT USED

For determination of acoustic P-wave and S-wave velocities a generator and a receiver of ultrasound with the following features are used:

- The conditioning of signal and pulse generation:
  - digitally controlled pulse generator and receiver with antialiasing filter;
  - acquisition board with maximum frequency of 20 MHz and a resolution of 12 bits with eight areas of frequency (156 kHz, 312 kHz, 625 kHz, 1.25 MHz, 2.5 MHz, 5 MHz, 10 MHz and 20 MHz);
  - receiver with frequency bandwidth of 10 MHz;
  - amplitude selected by user;
  - pulse generation for less than 5 nanoseconds.
- Connecting to the computer and data acquisition:

– eight analog inputs with antialiasing filter of 200 Hz;
– acquisition board with A/D conversion with 12 bit resolution, ± 10 V input (10 kHz sampling rate);
– two channels D/A for the output of P and S wave velocities to a external acquisition system or to a control system.

- Data acquisition unit for the ultrasound speed:
  – microprocessor system for improving and processing of the digital signal;
  – waveform storage;
  – filtering;
  – spectral analysis;
  – computer controlled selective switching between the reception sensors of the S and P waves;
  – automatic calculation of speed through the following methods:

a) absolute threshold;
b) relative threshold of the maximum amplitude;
c) relative threshold of the first arrival;
d) first arrival;
e) tangent to the first arrival.

The method used for speed determination was the first arrival.

In Fig. 3 the unit for signal generation, conditioning and reception of ultrasound (c), planar sensor for P and S wave velocities (a) and the group receiver-sensor mounted in measuring device for a soil sample (b) are presented.

3.2. RESULTS

The observed elastic anisotropy in peridotite samples increases proportionally with olivine content and crystal size. Thus, the porphyric peridotite with olivine content over 70% has elastic anisotropy of up to 7%. The average elastic anisotropy for lherzolites is 4% (Fig. 6).

For the amphibole pyroxenites the anisotropy decreases to 1.9–2%. For eclogitic samples the anisotropy varies from 0.9% to 1.4% (Fig. 7). This variation is due to the increase of omfacit content and with the degree of its orientation.

The velocities of the acoustic compressional wave determined for peridotitic samples vary between 8.34 and 8.44 km/s (Fig. 4, Table 1, section 1). This variation is due to variation of olivine content and degree of orientation of the crystals. The relatively restricted range of speed values is due to the general high content of olivine, regardless of the texture and structure of the rock.

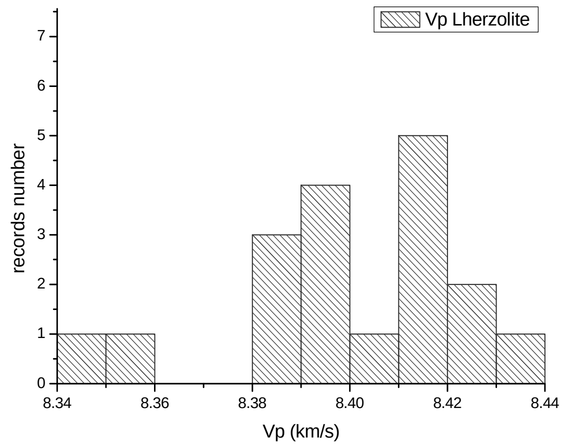

Fig. 4 – Histogram of P-wave propagation velocities determined in the laboratory for lherzolite.

Velocities in eclogitic rocks vary on a smaller range (Fig. 5), as a consequence of the fact that the element that can influence this change is the amount of garnet in rock and less the degree of orientation of the anisotropic contained minerals. Note that for this test we looked for eclogitic samples as they are affected to a small extent by any type of alteration processes.

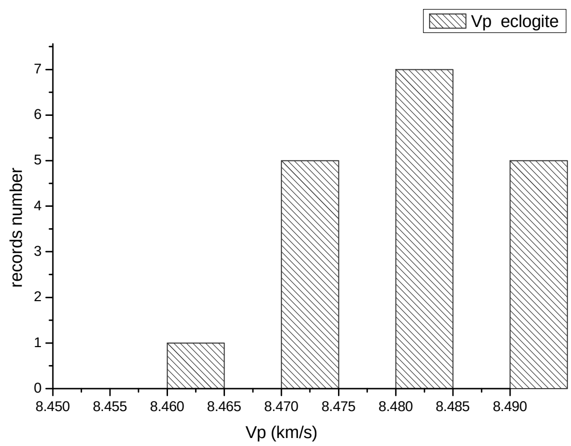

Fig. 5 – Histogram of P-wave propagation velocities determined in the laboratory for eclogite.

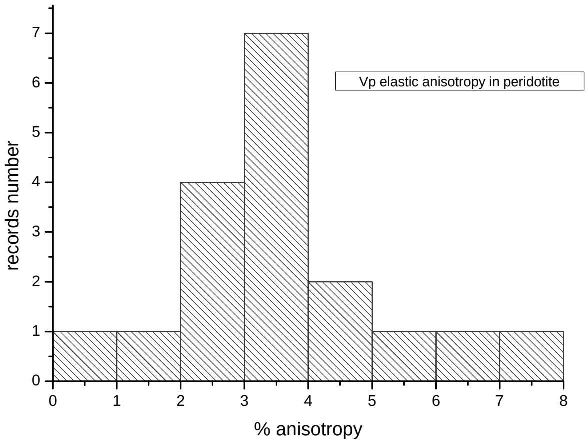

Fig. 6 – Histogram of the elastic anisotropy for the P waves in peridotite determined in laboratory.

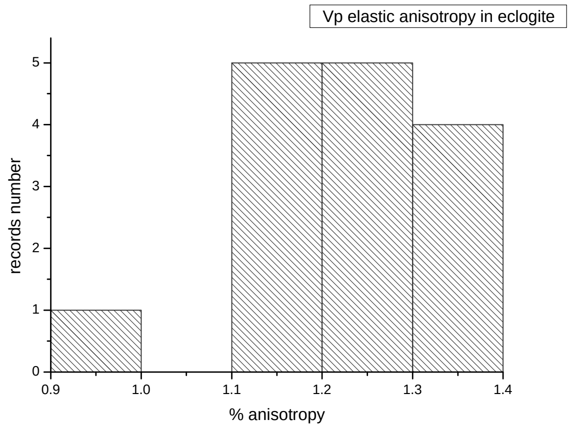

Fig. 7 – Histogram of P wave propagation velocity anisotropy in eclogite determined in the laboratory.

Table 1

Compressional and shear waves velocities, measured by ultrasound with frequency of 5 MHz for the samples of peridotite xenoliths from Racoş and eclogitic samples

Sample	**Vp km/s**	**Vs km/s**	**Vp/Vs**	**Vp averaged**	**vp/vs averaged**	**Vs averaged**
R1p position1	8.42	4.78	1.761506	8.3961	1.763484	4.7611
R2p	8.41	4.77	1.763103			
R3p	8.39	4.75	1.766316			
R4p	8.38	4.76	1.760504			
R5p	8.35	4.75	1.757895			
R6p	8.38	4.75	1.764211			
R1p position2	8.22	4.68	1.75641	8.2022	1.750586	4.6856
R2p	8.21	4.65	1.765591			
R3p	8.2	4.7	1.744681			
R4p	8.19	4.66	1.757511			
R5p	8.22	4.71	1.745223			
R6p	8.21	4.73	1.735729			
R1p position3	8.2	4.72	1.737288	8.1	1.712903	4.7289
R2p	7.8	4.7	1.659574			
R3p	8.2	4.69	1.748401			
R4p	8.3	4.74	1.751055			
R5p	8.1	4.69	1.727079			
R6p	8.1	4.76	1.701681			
Pga1 position1	7.89	4.63	1.704104	7.8993	1.702941	4.6387
Pga2	7.87	4.64	1.696121			
Pga3	7.92	4.65	1.703226			
Pga4	7.89	4.65	1.696774			
Pga5	7.89	4.64	1.700431			
Pga1 position2	7.8	4.65	1.677419	7.8073	1.67949	4.6487
Pga2	7.81	4.66	1.675966			
Pga3	7.82	4.64	1.685345			
Pga4	7.79	4.63	1.682505			
Pga5	7.78	4.64	1.676724			
Sample	Vp km/s	Vs km/s	Vp/Vs	Vp average	vp/vs average	Vs average
Pga1 position3	7.78	4.66	1.669528	7.76	1.668105	4.652
Pga2	7.74	4.63	1.671706			
Pga3	7.77	4.66	1.667382			
Pga4	7.77	4.66	1.667382			
Pga5	7.75	4.64	1.670259			
Ecg1 position1	8.48	4.78	1.774059	8.479	1.800181	4.7093

Table 1 (Continued)

Ecg2	8.47	4.68	1.809829			
Ecg3	8.48	4.7	1.804255			
Ecg4	8.48	4.69	1.808102			
Ecg5	8.47	4.71	1.798301			
Ecg6	8.49	4.72	1.798729			
Ecg7	8.47	4.66	1.817597			
Ecg8	8.49	4.69	1.810235			
Ecg9	8.47	4.68	1.809829			
Ecg10	8.49	4.7	1.806383			
Ecg1 position2	8.43	4.66	1.809013	8.427	1.811353	4.6523
Ecg2	8.44	4.66	1.811159			
Ecg3	8.42	4.64	1.814655			
Ecg4	8.43	4.65	1.812903			
Ecg5	8.41	4.64	1.8125			
Ecg6	8.42	4.65	1.810753			
Ecg7	8.42	4.65	1.810753			
Ecg8	8.43	4.66	1.809013			
Ecg9	8.43	4.65	1.812903			
Ecg10	8.43	4.65	1.812903			
Ecg1 position3	8.37	4.7	1.780851	8.3751	1.779285	4.707
Ecg2	8.375	4.72	1.774364			
Ecg3	8.373	4.7	1.781489			
Ecg4	8.377	4.71	1.778556			
Ecg5	8.375	4.7	1.781915			
Ecg6	8.374	4.69	1.785501			
Ecg7	8.375	4.71	1.778132			
Ecg8	8.376	4.7	1.782128			
Ecg9	8.376	4.72	1.774576			
Ecg10	8.375	4.71	1.778132			

Velocities determined in the laboratory can be affected by impurities from the host rock (alkali basalt) kept on the surface of the analyzed sample. These impurities may reduce the propagation velocity by up to 0.5 km/s for Vp and 0.7 km/s for Vs.

The speeds above have been corrected for the depth of 45 km for lherzolites and 50 km for eclogites according to the algorithm presented by Anderson in 1989.

Velocities Vp and Vs for samples studied by Vaseli *et al.* (1995) were also calculated. The calculation was done for a depth of 40 km and a geothermal gradient of 20 degrees per kilometer, because most samples investigated (21 of 28) were the spinel lherzolite with different structural varieties. Most of the structural varieties studied by these authors, and those processed for the preparation of this paper are anisotropic, showing a preferential orientation of the non isometric minerals. Some mineral segregation is present too. The elastic waves velocities and the elastic coefficients of these rocks have been calculated using a program created by Hacker & Abers (2004) with the assumption that they are perfectly isotropic. Results for four samples of garnet and spinel pyroxenite (eclogitic) are presented in Tables 2 and 3.

Table 2

Physical properties and water content of pyroxenite samples, calculated for the pressure of 1.5 GPa and temperature of 800°C

Sample	PGS1	PGS2	PGS3	PGS4
P (GPa)	1.5	1.5	1.5	1.5
T (°C)	800	800	800	800
H2O (wt%)	0.0	0.0	0.0	0.0
rho (g/cm3)	3.40	3.40	3.40	3.40
Vp (km/s)	8.56	8.52	8.46	8.50
Vs (km/s)	4.81	4.78	4.74	4.77
K (GPa)	144	143	141	143
G (GPa)	79	78	76	77
Poissons	0.27	0.27	0.27	0.27

These values were compared with the mean velocity from measurements obtained with ultrasound, the latter being corrected to a temperature of 800 degrees and pressures of 1.5 GPa for peridotite and respectively 1.7 GPa for pyroxenite and eclogite. This correction was applied considering the average density of the cover formations at about 2.7 t/m^3. The geothermal gradient used was of 20 degrees/km.

Table 3

Physical properties and water content of pyroxenite samples, calculated for the pressure of 1.7 GPa and temperature of 800°C

Sample	PGS1	PGS2	PGS3	PGS4
P (GPa)	1.7	1.7	1.7	1.7
T (°C)	800	800	800	800
H2O (wt%)	0.0	0.0	0.0	0.0
rho (g/cm3)	3.40	3.40	3.40	3.40
Vp (km/s)	8.58	8.54	8.47	8.52
Vs (km/s)	4.82	4.79	4.74	4.77
K (GPa)	145	144	142	143
G (GPa)	79	78	77	78
Poisson ratio	0.27	0.27	0.27	0.27

Following the applied corrections it was found that average speed results from ultrasonic measurements are comparable with those obtained by calculation and are also comparable to those from the Pn and Sn wave study conducted by Ivan (2004).

Then we recalculated the speeds determined by the program, taking into consideration the degree of anisotropy, determined by ultrasound, for each sample studied.

The results of recalculation showed that for given thermo-barometric conditions, the velocities of acoustic compressional wave are within the range 7.12–8.07 km/s for peridotite and pyroxenite samples and in the range 8.47–8.48 for the clinopyroxenite with spinels and garnets. The latter has a higher speed than eclogitic samples examined with ultrasound (8.2–8.32 km/s), probably due to the high content of spinels.

4. CONCLUSIONS

In this study we observed that the elastic wave speed in peridotite determined by ultrasound is comparable to those determined *in situ* and those computed based on modal compositions. This can be considered a confirmation of peridotite composition, mainly lherzolitic, of the upper lithospheric mantle for certain areas in Romania.

Velocities determined by ultrasound on eclogitic samples are lower than those determined *in situ* in areas considered as having eclogitoid type lithology. The latter are comparable to those calculated for pyroxenites with garnet and spinels based on modal compositions. This suggests that lithology true for areas with high velocity contrast at Mohorovicic discontinuity is of the piroxenitic with garnet and spinel type. In this case the eclogite tests were inconclusive.

Laboratory techniques for determining the velocity and elastic anisotropy of rocks provide very useful information for building geological models of the main areas of discontinuity in the lithosphere.

Based on information obtained by studying the propagation velocities of elastic waves from crustal earthquakes whose epicenters are located at distances of up to 10 degrees (1100 km) to the measuring points, one can obtain the seismic velocities distribution *in situ* for Mohorovicic discontinuity. With this information and linking it with velocities determined in the laboratory on various xenoliths and structure information, mineralogical composition and thermo-barometric conditions of stability of the studied samples, one can generate a petrographic and structural model for discontinuity areas (in our study Mohorovicic discontinuity), which be extended to certain regions within the lithosphere.

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