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COMPARISON OF FIELD AND LABORATORY SEISMIC VELOCITY ANISOTROPY MEASUREMENT (SCALING FACTOR)

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ABSTRACT

P-wave velocity anisotropy of rocks is often investigated by laboratory methods. The extrapolation of the laboratory results to larger rock units requires comparison with direct field measurements. Physical properties of deep-originated rocks were performed on mantle-derived peridotite from the Ivrea zone (Northwestern Italy). These rocks were exhumed by tectonic processes during collision orogeny up to the Earth's surface. The direct surface seismic measurements of elastic waves velocity were realized by means of shallow seismic refraction method on the outcrop of peridotite. The measuring base was about 10 m long.

Laboratory seismic anisotropy measurement was realized on rock samples from the same outcrop. The geographically oriented spherical samples with diameter 50 mm were radiated by elastic waves in 132 directions under confining stress from atmospheric level up to 200 MPa.

Laboratory and field values of the anisotropy of seismic wave velocities were compared and different scales of measurements were evaluated. The field measurements used frequency about 1 kHz whereas the laboratory measurement used 700 kHz radiation. Field measurements proved relatively high value of anisotropy P-wave propagation – 25%, while laboratory experiments only 1.5%. This difference is caused by different reason of anisotropy. Laboratory samples contain only microcraks, which represents nearly continuum with regard to ultrasound wave length (11 mm). Rock massif, however, contains beside mickrocraks also cracks with comparable size of applied seismic wave length (10 m).

KEYWORDS: seismic velocity, anisotropy, shallow seismic refraction method, ultrasound radiation

1. INTRODUCTION

The laboratory research into the anisotropy of the propagation velocity of elastic waves in ultrabasic rocks has been conducted in the Laboratory of Physical Properties of Rocks for a number of years. The purpose of these studies is to determine the changes in the orientations of the directions of the maximum and minimum propagation velocity of ultrasonic waves with increasing hydrostatic pressure. The device developed and the method introduced by Pros and Podroušková (1974), Pros et al. (1998) can be used to simulate the pressure conditions, corresponding to the deposition of the rocks at a depth of about 20 km, i.e. roughly at a depth, from which the studied rocks were brought to the surface. Earlier papers reported the results of determining the velocities of propagation of P-waves and anisotropy coefficient and their changes in dependence on the direction of sounding and on the acting pressure. Laboratory experiments proved that the rock structure has the principal effect on the anisotropy of the propagation velocity of ultrasonic waves. Measurements of neutron diffraction (Ivankina et al., 1999) proved that the preferred orientations of minerals predetermine the maximum and minimum velocities of ultrasonic waves and effect the magnitude of elastic anisotropy. The extrapolation of the laboratory results to larger rock units, however, requires comparison with direct field measurements (Přikryl et al., 2004). Field measurements and rock sampling for laboratory tests were carried out in the Ivrea zone – north-western Italy.

2. GEOLOGICAL SETTING

The Ivrea zone is the westernmost and most highly metamorphic part of the Southern Apls (Belluso et al., 1990). It forms an arc-shaped outcrop, almost 200 km long and up to 20 km wide, extends from Locarno, Switzerland in the northeast to Ivrea, Italy in the southwest. The zone is bounded on the northwest by the Insubric Line, a major tectonic dislocation which separates it from Alpine metamorphic rocks of the Western Alps (Belluso et al., 1990).

The Ivrea zone is composed of pre-Alpine strong metamorphic rocks. Their metamorphic grade increases from amphibolite facies in the southeast to granulite facies in the northwest (Schmid, 1967;

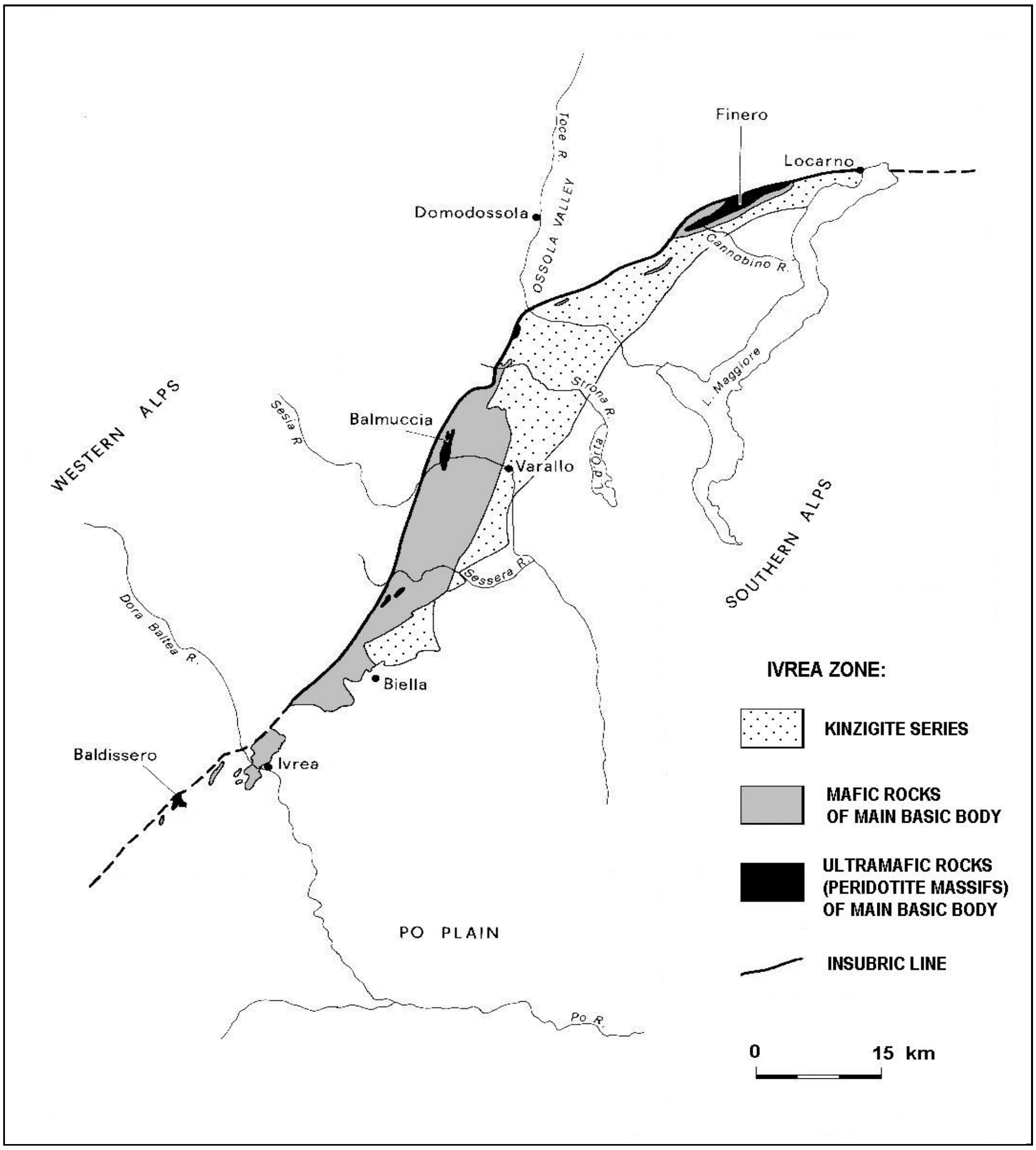

Fig. 1 General geological sketch-map of Ivrea zone (modified after Belluso et al., 1990).

Zingg, 1980). Lithologically, the Ivrea zone consists of a metasedimentary series and of a main basic body, with related ultramafites (Fig. 1) (Rivalenti et al., 1981). Metasedimentary (Kinzigite) series is mainly composed of metapelites (alternating paragneisses and micaschists) with subordinate marble and metabasite intercalations. Main basic body is complex of mafic rocks primarily formed of granulitic rocks, namely metagabros with subordinate ultramafic rocks - peridotites and pyroxenites (Rivalenti et al., 1981). There are three large peridotite masiffs along the Insubric Line – Baldissero, Balmuccia and Finero. The peridotites are interpreted as slivers of subcrustal litospheric mantle material (Lensch, 1968; Shervais, 1979; Burlini and Fountain, 1993).

For our detailed in-situ and laboratory measurements we choose the ultramafite peridotite massif at Balmuccia. The Balmuccia peridotite massif is crudely tabular and ranges up to about 700 m in thickness, with the long dimension of 4.5 km aligned nearly north–south. The peridotite appears to have been tectonically emplaced in the mafic granulite + interlayered calc-shist terraine of the lower Ivrea zone in a largely solid state (Ernst, 1978).

The dominant rock-type of the Balmuccia peridotite massif is a medium- to coarse-grained, porphyroclastic spinel lherzolite (Shervais, 1979). Harzburgites and dunites are subordinate (Rivalenti et al., 1981). Websterite, pyroxenite and gabro dikes and pods are also common in the Balmuccia peridotite (Lensch, 1976).

According to modal composition analyses in Ernst (1976), the Balmuccia lherzolites contain olivine as a main rock-forming mineral (modal olivine ranges between 30 and 70 %), orthopyroxene (15 – 30 %) and clinopyroxene (4 – 35 %). The lherzolites

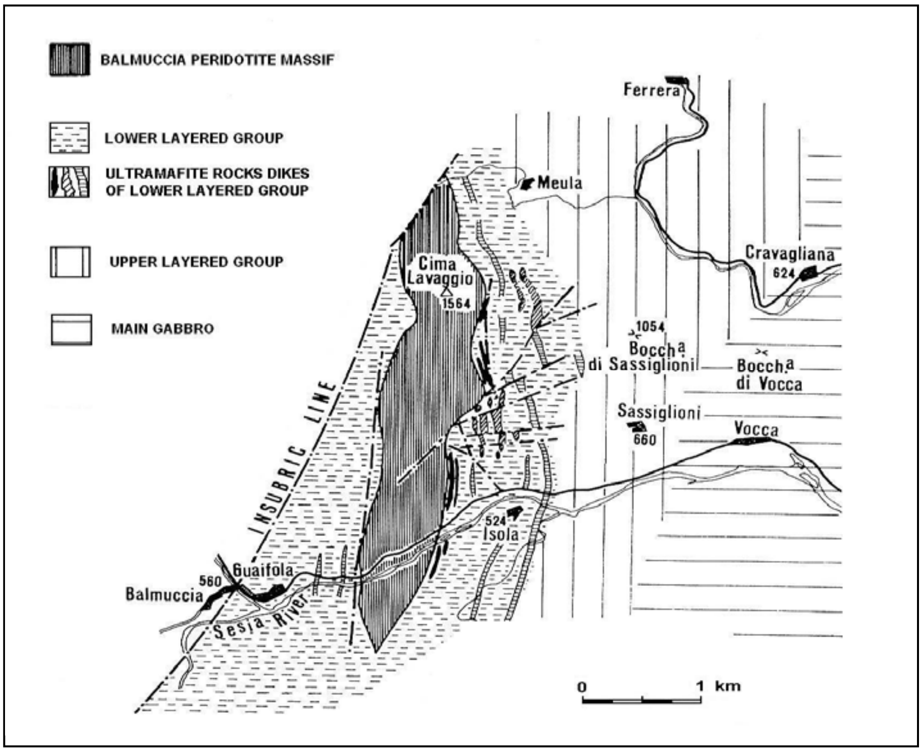

Fig. 2 Outline geological map of part of the Main Basic Body with the Balmuccia massif (modified after Rivalenti et al., 1981).

uniformly carry between 3 and 6 % interstitial spinel. Hornblende is a broadly distributed accessory mineral, and a few rocks contain basic plagioclase.

Real in-situ measurement and rock sampling for laboratory measurement were carried out in the southern part of Balmuccia massif at a flat outcrop of the lherzolite in the Sesia River Valley, between Balmuccia and Isola villages (Fig. 2).

Three systems of fractures were observed macroscopically at the surface of the outcrop. The first system is oriented from E to W. The fractures of this system are opened at the surface and distance between neighbouring fractures is about 20 cm. The second system of fractures running N to S consisted of tight fractures with a density of as much as 1 fracture per 10 cm in places. The third system of fractures, which could be observed macroscopically, was a system running from SW to NE. These fractures were tight and the distance between neighbouring cracks mostly exceeded 50 cm.

3. SEISMIC SURFACE MEASUREMENTS

Seismic field measurements were carried out with a 24-channel Geode engineering seismograph by Geometrics (USA) using a knock seismic energy source. The device enables the recording of seismic signals ranging in frequency from 1.75 Hz to 20 kHz. Since the measurements were carried out directly on the surface of the rock outcrop, and with a view to the expected high velocity, the sampling frequency chosen was 50 kHz. The geophones were staked out along two concentric circles, radii 1 and 2 m (Fig. 3). Twelve geophones were placed regularly in steps of 30 degrees along each circle. Standard, 24 Hz, vertical electrodynamic geophones were employed. To ensure good transmission of seismic energy, the geophones were stuck to the surface of the outcrop with plaster. The seismic energy was generated by striking a small metal plate with a 1-kg hammer. The predominant frequency of the recorded seismic waves was between 1 and 2 kHz. The time of impact, or of switching on the recording, was determined by means of the electric contact between the hammer and the metal plate. To determine the velocity of longitudinal seismic waves, the measurement was carried out with the point of impact in the centre of the circles. The spatial configuration in the locality enabled the seismic energy to be generated at another six points outside the circle of geophones, at a distance of 8 m from the centre of the geophone configuration (Points A to F, see Fig. 4).

The seismic wave velocity was determined from the slope of the travel-time curves. By measuring with the source in the centre of the circular configuration of geophones, the travel-time curves were constructed from four times, measured at four points along a straight line, running through the centre point of impact. This yielded a centre symmetrical image of the velocity distribution in dependence on the six directions of measurements (at steps of 30 degrees).

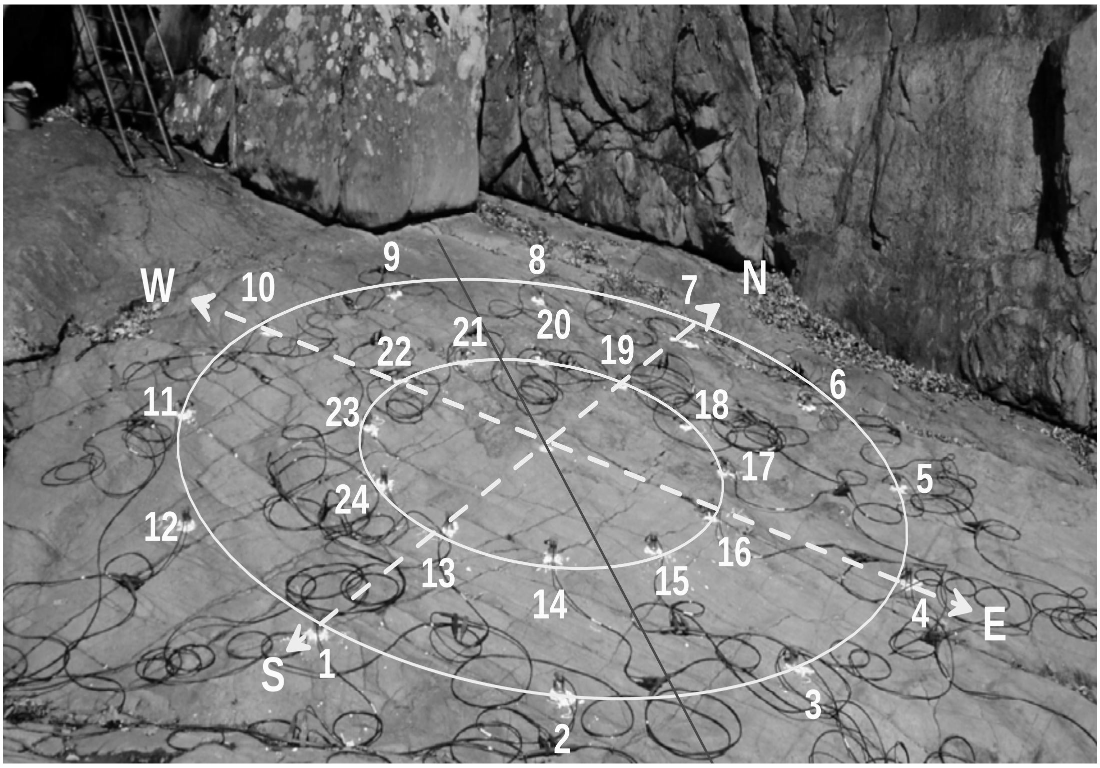

Fig. 3 Field measurement. The outcrop surface is flat with dip 20.4 degrees to SE, strike 43.3 degrees. 24 geophones are placed directly on the rock outcrop forming two circles with 12 geophones at 30 degree step.

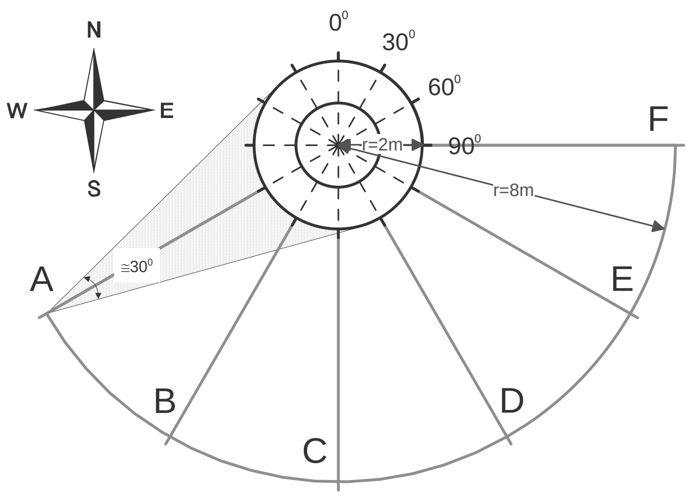

Fig. 4 Field measurement setup. 24 geophones forming two circles, each with 12 geophones at 30 degree with radii 1 m and 2 m. External sources are in points A to F in the distance 8 m from geophone circles centre-point.

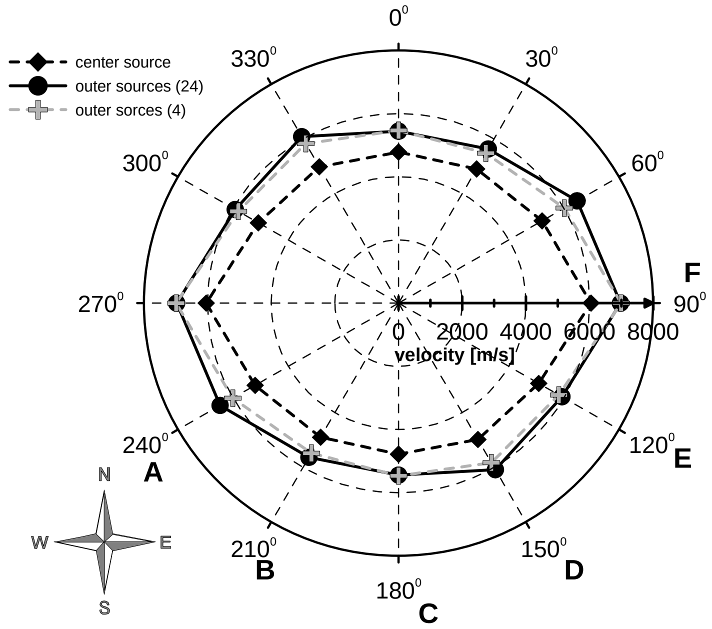

Fig. 5 Velocity of seismic waves from field measurement. Comparison of measurements with different scales.

The six external seismic sources at points A through F were also used to determine the centre symmetrical image of the velocity distribution. In this case, the velocity was determined from the four times determined at the points located on the straight line with the point of impact, on the one hand, and, on the other, also from all the time determined from all 24 geophones on the two complete circles, located within the angle of 30 degrees with its apex at the point of impact. By reducing their positions to correspond to a single travel-time curve, it was possible to determine the velocity by fitting a straight line to all 24 times on the reduced travel-time curve. The velocity, determined in this manner, does not correspond precisely to the direction determined by the point of impact and the geophone circle centre; however the method of calculation suppresses any possible effect of inhomogeneities of the medium in the neighbourhood of the separate geophones. In routine measurements of refraction seismology, this effect is usually eliminated by using direct and reversed travel-time curves, and calculating the velocity from the slope of the difference travel-time curve. With a view to the space available at the place of measurement, this method could not be applied. The velocities determined in dependence on direction are shown in Figure 5.

The velocities determined in various directions differ, and the velocity determined from the central source is lower than the velocity determined from the external sources. The dependence of velocity on the direction of propagation of seismic waves reflects the anisotropy of the medium. The field measurements enabled the anisotropy to be determined practically only in the plane of the outcrop surface. The anisotropy coefficient k of Birch (1961) was used to evaluate it quantitatively:

$$k = \frac{v_{\max} - v_{\min}}{v_{mean}} 100\%$$

where v_{mean} is the mean velocity, in this particular case determined as the arithmetic average of the velocities corresponding to all measured directions. The values of the maximum and minimum velocities and coefficients of anisotropy are summarized in Table 1. The frequency analysis of the signals recorded during field measurements has indicated that the significant amplitudes in the spectra are located in the frequency interval 500 Hz to 2500 Hz. For the average propagation velocity of seismic waves of 6000 m/s (external source) the seismic wave displays a wavelength of 12 m to 2.4 m. For a velocity of 5000 m/s (the source is located in the centre of the geophone circle configuration) the corresponding wavelengths range from 10 m to 2 m. The spectra of the records, corresponding to the central source, fall within the interval of 1000 to 2500 Hz. The records from more distant sources are usually within a broader frequency interval, i.e. about 500 to 2500 Hz. At some of these points of impact, however, the records lack the higher frequencies (maximum signal frequencies are about 1000 Hz).

Table 1 Field measurement – velocities and coefficient of anisotropy for different measurement setups.

measurement	v_{min} [km/s]	v_{mean} [km/s]	v_{max} [km/s]	**k** [%]
24 geophones	5.442	6.088	6.971	25.1
4 inline geophones	5.466	5.932	6.989	25.7
central source	4.780	5.166	6.044	24.5

Table 2 Laboratory analysis of anisotropy – velocities and coefficient of anisotropy with pressure.

p **[MPa]**	v_{min} [km/s]	v_{mean} [km/s]	v_{max} [km/s]	**k** [%]
0.1	7.603	7.836	8.122	6.6
10	7.627	7.858	8.135	6.5
20	7.662	7.888	8.149	6.2
50	7.685	7.918	8.162	6.0
100	7.709	7.956	8.216	6.4
150	7.745	7.997	8.243	6.2

Table 3 Laboratory radiation measurement – velocities and coefficient of anisotropy in outcrop surface plane.

measurement	v_{min} [km/s]	v_{mean} [km/s]	v_{max} [km/s]	**k** [%]
laboratory, outcrop surface plane	7.690	7.728	7.800	1.4

4. LABORATORY MEASUREMENTS OF VELOCITY ANISOTROPY

The laboratory measurements of velocity anisotropy using the method of ultrasonic sounding of signals through a spherical rock specimen, 5 cm in diameter (Pros and Podroušková, 1974; Pros, 1977) are conducted in many directions and enable the directional dependence of velocity of longitudinal waves to be expressed with the aid of lines of equal velocity on the surface of a sphere. Sampling frequency of signals used was 100 MHz, i.e. 10 ns in time domain. The measurements, moreover, can be carried out under conditions of different hydrostatic pressure acting on the specimen being scanned. The changes of anisotropy as a result of hydrostatic pressure may be interpreted as a manifestation of the closing of existing systems of cracks and, for higher pressures, as the effect of pressure on the elastic constants of rocks (Pros et al., 1998; Pros et al., 2003; Přikryl et al., 2007; Ullemeyer, 2006).

In this particular case, an oriented specimen was collected from the studied rock outcrop, and a sphere was made from it for ultrasonic sounding. The sounding was carried out for hydrostatic pressures ranging from 0.1 MPa (normal atmospheric pressure) to 150 MPa (Table 2).

The variations of velocity with pressure (Table 2) are evidence that the specimen was minimally disrupted by cracks or systems of cracks. Therefore, under increasing hydrostatic pressure no velocity increase was observed, which would otherwise have been caused by their closing. In the table, the velocity anisotropy is evaluated only in terms of the anisotropy coefficient. The latter remained practically unchanged during loading. The sounding in many directions, of course, also enabled the determining of the spatial distribution of velocity across the sphere surface. This indicates that the direction of the highest velocity is roughly perpendicular to the outcrop surface. In the plane perpendicular to this direction (i.e. in the plane of the outcrop surface) on the other hand, practically minimal velocities were observed, and the velocities in this plane displayed a very small scatter. The difference between the lowest and the highest velocity was 110 m/s, which, given the average velocity determined in this plane of approx. 7730 m/s, is less than 1.5 % of this velocity.

The laboratory determined velocities under a pressure of 0.1 MPa were used for comparison with field measurements. Moreover, only the data corresponding to the direction of sounding on the sphere in the plane corresponding to the orientation of the outcrop plane in the field (Table 3) were used for comparison field and laboratory results.

In laboratory sounding, the frequency of the signal employed is 700 kHz. The wave length of the elastic wave, whose velocity is 7800 m /s (average of scanned velocities), is 11 mm.

5. DISCUSSION

The field measurements of velocities have indicated that the velocities of waves propagating along a path up to 2 m in length (central position of seismic source) and along a path up to 10 m in length (external source) differ; the measurements with a longer measuring base displayed velocities higher by about 20% than the short base. The frequencies of the recorded seismic waves differ for the separate impacts, which most probably depend on the conditions under which the seismic waves are generated (e.g., the absence of higher frequency components at some of the external impact points). However, the filtering of high frequencies at all external sources was not observed. Similarly, no regular dependence between the prevailing frequency and observed seismic velocity was observed.

The rock massif in the immediate vicinity of the surface is, to a certain extent, affected by temperature variations, freezing in winter and similar effects. These effects are responsible for the mechanical disturbance of the massif by cracks, which increases due to exogenous factors. From a seismological point of view, the near-surface part of the massif may appear to be a medium with negligible increase of velocities of seismic waves with depth. In this kind of medium, seismic waves penetrate deep down, propagate along curved paths and, due to this curvature, they reach the surface. These waves, which appear in the first onsets, are referred to as diving waves (Sheriff, 2003). The depth of penetration of the rays depends on the vertical velocity gradient and on the distance between the source and geophone. In case of the central seismic source, whose distance from the geophone is 1 to 2 m, one may consider relatively shallow penetration of seismic rays into the rock massif, and the seismic wave then propagates mostly through the disturbed part of the massif. Hence, its velocity is the smallest. As regards rays generated at a distance of 8 m from the centre of the circle of geophones, the penetration depth is larger; the rays propagate through a medium less affected by surface effects. Moreover, existing cracks may be below the groundwater level and they can be filled by water. Therefore the higher velocities are recorded in the case external seismic sources.

The velocity anisotropy, determined by all three field measurement variants, is practical identical. The differences are negligible in comparison with accuracy of velocity determination. The maximum P-wave velocity was in direction from east to west and minimum velocity was in direction from north to south. In the case of external sources measurements and the comparison of the variants with 4 and 24 geophones only shows that the apparent velocities, determined from travel-time curves, can be consider to be the real velocities. If the measurements with external sources and the central source are compared, the rays penetrating to different depths, the same anisotropy is evidence that the effect of different systems of cracks with depth decreases at the same rate. From the point of view of the effect of the cracks on velocity, therefore, their density is probably more important than the degree to which they are opened or closed at the surface. The density of the cracks does not probably change with depth, whereas open cracks can usually be expected to have a large effect on the surface, only to drop off with depth.

The scale factor between the laboratory measurements and measurements in situ was roughly 1:200. The diameter of the measured sphere specimen was 50 mm, and the measuring base of seismic refraction was 10 000 mm, the wave lengths were at a ratio from 1:200 to 1:1200.

The comparison of the laboratory and field measurements is based on the comparison of the velocities measured under laboratory and field conditions. Of the laboratory values, only the velocities corresponding to the direction of sounding of the seismic waves in the plane of the rock outcrop can be used. Since the specimen was collected as an oriented specimen, the position of this plane on it can be determined. The actual laboratory sounding is carried out at steps of 15° along the meridians and parallels. The obtained values are then approximated on the sphere surface by a function of two variables. Lines of equal velocity are plotted on the sphere surface which makes possible to obtain an approximate velocity graph in any plane of sphere specimen, i.e. in the plane, the orientation of which corresponds to the surface of the field outcrop. This velocity graph is shown in Figure 6.

The laboratory velocities display practically no anisotropy in the plane of the outcrop; the differences in velocities are practically at the level of their measuring errors. Field data, obtained by using external seismic sources, were used for comparison, because they are closer in terms of velocity to the laboratory velocities. The specimens were collected directly from the surface of the rock outcrop and, therefore, it might seem more suitable to compare the laboratory velocities with the results of the field measurements related to the central source, because the rays penetrated to a smaller depth in this case. However, one must bear in mind that a specimen, 5 cm in diameter, represents an undisturbed part of the massif without any macroscopic cracks at all. From the point of view of mechanical properties, therefore, the more appropriate is the medium of the massif at a certain depth, where the cracks are closed and filled with water, and their effect on the velocity of propagating elastic waves is thus smaller. The compared laboratory and field velocity values are given in Table 4.

The values of velocity, determined in the specimen, is greater then the corresponding field velocity about 12 and 41% (comparison of maximum and minimum velocities, respectively – Table 4). At the same time, it was found that the field measurements displayed considerable velocity

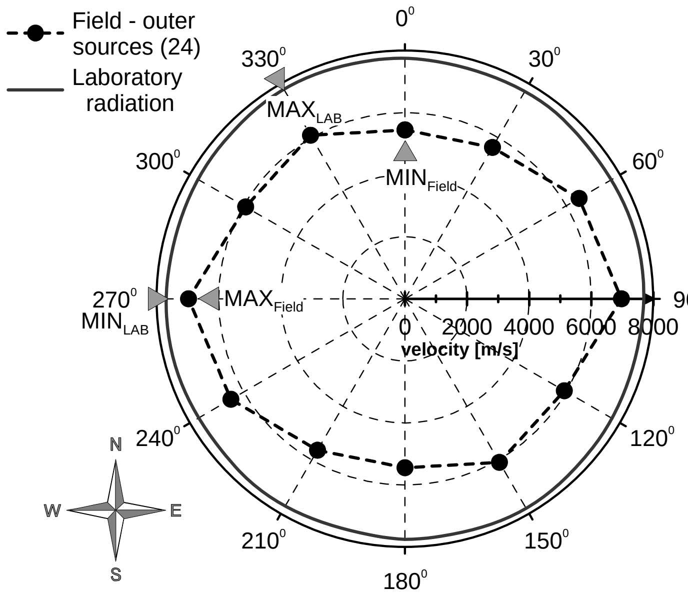

Fig. 6 Comparison of velocities from field and laboratory measurements.

Table 4 Comparison of field and laboratory velocity measurement.

	v_{min} [km/s]	v_{mean} [km/s]	v_{max} [km/s]	k [%]
Field measurement	5.442	6.088	6.971	25.1
Laboratory measurement	7.690	7.728	7.800	1.4
Difference [%]	41	27	12	

anisotropy, which was not in evidence in laboratory sounding (we are comparing the results in the plane of the field measurements). In the given case, the velocity anisotropy apparently reflects the different effects of the separate crack systems on the velocity of elastic waves. The wave length of a seismic wave in field measurements ranges from 2.4 to 12 m. One could then expect its sounding to be unaffected by inhomogeneities of the order of units of meters. A system of parallel cracks with a density well below one meter, however, clearly affects the whole massif and, hence, also its elastic properties also for waves of such lengths.

In the given case, the structure of the undisturbed rock in the outcrop plane is omni-directional, free of micro disturbances, which perhaps means that no directions of future preferred deformation, observed in other cases, exist in it (Přikryl et al., 2004). In such a case, the directions of macroscopically observable systems of cracks could correspond fully to the orientation of the force field, which was responsible for its generation. This would then provide great support to the studies of the forces, which took part in the dislodgement of the whole geological body, or which acted on it in the geological past. This hypothesis can also be verified by laboratory loading tests of oriented rock specimens.

6. CONCLUSIONS

- Velocities determined in laboratory are higher than velocities determined in field
- Velocities from samples are determined by modal composition and preferred crystallographic orientation, at low confining pressure they are affected by microcracks
- Field velocity measurement reflects the distribution of cracks
- There is substantial difference between field- and laboratory-determined velocity anisotropy
- The common study of laboratory and field anisotropy can reveal their different sources

- Scaling factor is affected dominantly by different sampling size. Laboratory samples contains microcraks and represent nearly continuum from point of view of applied wave length, however rock massif contains beside mickrocraks also cracks with comparable size as applied seismic wave length.

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