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# Effects of foliation and microcracks on ultrasonic anisotropy in retrograde ultramafic and metamorphic rocks at shallow depths

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ABSTRACT

We have conducted ultrasonic measurements on cylindrical specimens of serpentinite, talc, granite gneiss, biotite schist, and amphibole schist from rock samples taken in the mid-west region of South Korea. Two samples were prepared from each rock block by coring along and across the foliation. Compressional and shear wave velocities were measured along the cylindrical samples at different levels of confining pressure up to 70 MPa at room temperature. Our test results show that the foliation is a primary (or intrinsic) parameter of ultrasonic anisotropy because both velocities along the foliation are considerably higher than those across the foliation, regardless of cell pressure (with the sole exception of talc). The ultrasonic anisotropy varies with confining pressure, and this behavior is the result of the gradual closure of microcracks with increasing confining pressure. The preferred orientation of mechanically induced open cracks is a secondary (or extrinsic) parameter of ultrasonic anisotropy, which disappears when the cracks are completely closed while the primary parameter remains. The secondary parameter affects the lithological anisotropy in one of the two ways: either monotonically raising or monotonically lowering the magnitude of anisotropy with a rise in confining pressure. These two distinct behaviors result from differing angles of the preferred orientation of microcracks with respect to the foliation. These differing angles are possibly related to local variations in the late brittle deformation in the study area.

## 1. Introduction

Because there is a lack of direct ac\cess, most studies of the mineral composition, physical properties, and structure of the interior of the Earth have relied exclusively on seismological data from earthquakes and artificial explosions. Inversion of the seismic time–distance curve yields an elastic wave velocity profile as a function of depth and distance (Garland, 1979). The velocity is closely related to rock properties, which are coupled with lithological and physical parameters in a complex manner (Kern, 1990; Kern et al., 1991). For a better understanding of how these parameters control the ultrasonic characteristics of rock mass, we need laboratory scale seismic measurements that can be interpreted with an understanding of mineral compositions and textures under controllable physical (e.g., stress and temperature) conditions (Christensen, 1966; Christensen and Fountain, 1975; Jackson and Arculus, 1984; Kern, 1990; Kim et al., 2012). The empirical relations between seismic data and the lithological characteristics of ultramafic rocks, which are rarely exposed at the surface of the Earth, are of fundamental importance when investigating the nature of the upper mantle (Christensen, 1984).

Seismic anisotropy in the lithosphere is a useful clue to identifying transition zones, understanding geodynamic processes, and monitoring earthquake cycles (Christensen and Lundquist, 1982; Crampin et al., 1999; Montagner and Guillot, 2002). The ultrasonic anisotropy of rock comes intrinsically from the lattice-preferred orientations of rock-forming crystals and their textural arrangements (Babuška, 1981; Ben Ismaïl and Mainprice, 1998; Bezacier et al., 2010a; Christensen, 1984; Thill et al., 1969). Additionally, mechanical parameters such as rock fractures, cracks, and distortional deformations that result from tectonic and orogenic movements can also be the sources of ultrasonic anisotropy (Kern, 1978). It has been suggested that a systematic arrangement of microcracks, induced by deviatoric stress, may have a secondary effect on the anisotropy of rocks (Anderson et al., 1974; Nur, 1971; Nur and Simmons, 1969; Sayers et al., 1990; Siegesmund et al., 1991; Zatsepin and Crampin, 1997). For example, an extensive dilatancy-induced seismic anisotropy that results from the distribution of stress-aligned microcracks has been observed at various earthquake sites (Crampin, 1987; Crampin et al., 1980, 1999; Scholz et al., 1973; Silver and Chan, 1988). The secondary effects vary with the physical conditions, whereas the intrinsic anisotropy does not change, unless the rock is subjected to dynamic recrystallization at high temperatures and pressures (Siegesmund and Vollbrecht, 1991).

We have measured the compressional and shear wave velocities along and across the foliation of serpentinized ultramafic rocks and

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metamorphic country rocks that outcrop near Hogseong in the mid-west region of South Korea (Fig. 1). The velocity data have been used to determine the elastic modulus set of transversely anisotropic rocks (Song et al., 2004). The present study focuses on the ultrasonic anisotropy of foliated rocks, but we are also interested in the effects of confining pressure on the ultrasonic anisotropy because it might lead to the closure of microcracks. The foliation, a lithological anisotropy parameter, originated from recrystallization during metamorphism, while the microcracks, referred to here as a mechanical anisotropy parameter, were induced by brittle tectonic deformation after the metamorphism (Kern, 1990; Kern et al., 1991). The ultimate goal of our research is to understand the different characteristics of the ultrasonic anisotropy that result from these different source parameters, and also to understand the coupling between the two parameters in geologic processes. Our laboratory experiments could be used to interpret the velocity structure of the upper crust, taking the elastic anisotropy resulting from rock fabric observations and mechanical behaviors into account.

## 2. Geology of sample locations

Metamorphosed ultramafic rocks, mainly serpentinites, occur in the form of discontinuous isolated lenticular intrusive bodies that are parallel to the strike of the large faults exposed in the mid-west area of South Korea (Fig. 1). The area is composed of a Precambrian gneiss complex, overlain by the Jurassic Nampo Group, intruded by Jurassic diorites and granites, and covered by Quaternary alluvium (Woo and Suh, 2000). The Precambrian metamorphic rocks are divided into two units: the Weolhyeonri meta-sedimentary rocks and the Deogjeongri granite gneiss. The latter intrudes the former (Woo and Suh, 2000). The Weolhyeonri Formation consists of biotite schist and amphibole schist, the latter of which is mainly found near lenticular bodies of serpentinite. The granite gneiss, the most widely exposed rock type in the study area, is composed of quartz, plagioclase, alkali-feldspar, biotite, amphibole, and chlorite together with minor accessory minerals. A series of dextral strike-slip faults with a trend of about N10°E cut through all of the geologic sequences except the alluvium (Fig. 1). The foliation of the Precambrian metamorphic complex has a strike of N20–40°E and it dips 30–70°SE or NW.

The protolith of the serpentinite is inferred to have been alpine type ultramafic rocks such as dunite and/or harzburgite which originated from a slightly depleted upper mantle (30–40 km deep) and were emplaced in the crust along large thrust fault zones (Woo and Suh, 2000). Most bodies of serpentinite contain more than 50% serpentine, but some include relicts of the original minerals such as olivine, pyroxene, and chromite. The chemical compositions and physical properties of these rocks are the representative of the rocks of the upper mantle (Woo and Suh, 2000). The serpentinized ultramafic rocks were partly altered by hydrothermal processes along various fault and shear zones, where they provide economically useful ore deposits such as talc and asbestos.

Three blocks of serpentinite and a block of talc were taken from various talc and/or asbestos mines at different locations for ultrasonic velocity measurements (Fig. 1). We also collected samples of three different types of metamorphic country rock: a granite gneiss, a biotite schist, and an amphibole schist; to make comparisons with the serpentinite and talc specimens in terms of their ultrasonic characteristics (Suh et al., 2000). The blocks of serpentinite1, granite gneiss, and talc were obtained at locations greater than 10 km to the east of the fault system, and the other blocks, the serpentinite2, serpentinite3, amphibole schist, and biotite schist, were obtained near the strike-slip and thrust fault systems (Fig. 1).

## 3. Ultrasonic measurements

All of the blocks obtained for ultrasonic measurements are very obviously foliated, while any other anisotropic characteristics are not macroscopically visible (Song et al., 2004). With an assumption of transverse isotropy in the rocks, we measured the ultrasonic velocity in the two directions that are parallel and perpendicular to the foliation. Two samples were prepared from each of the seven blocks (serpentinite1, serpentinite2, serpentinite3, talc, granite gneiss, biotite schist, and amphibole schist) by drill-coring across and along the foliation (Fig. 2a). The core samples were cut at both ends, which then were polished to make good contacts for the ultrasonic transducers. The final dimension of each specimen was 5 cm in diameter and 10 cm in length. The ultrasonic measurements were conducted at the High-Pressure and

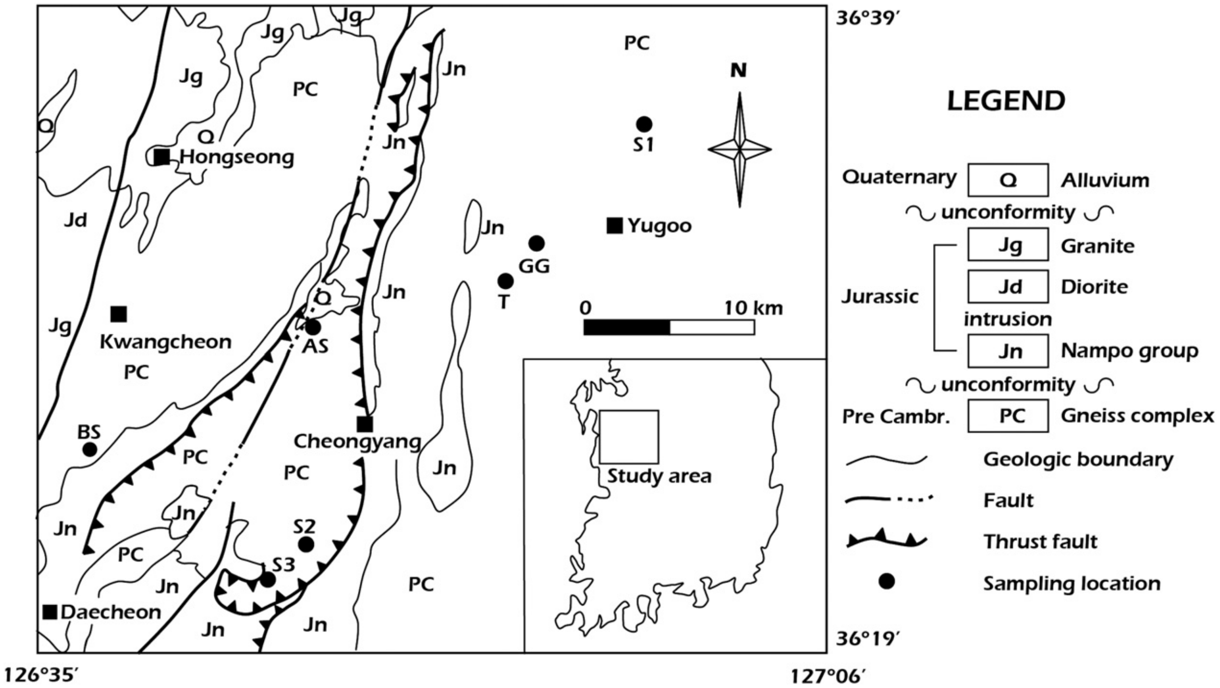

**Fig. 1.** Geologic map showing sample locations. S1, serpentinite1; S2, serpentinite2; S3, serpentinite3; T, talc; GG, granite gneiss; AS, amphibole schist; BS, biotite schist.