Rock Anelasticity Studies at High Pressure and Temperature

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Abstract

Geophysical techniques used in the exploration for the thermal structure of the Earth include heat flow measurements, seismic studies and electric and electromagnetic soundings. The goals of these geophysical explorations are to detect and interpret the anomalies defined in the physical quantities measured, and to derive thermal models of the Earth. To this end, knowledge of the physical properties of in-situ rocks is required.

In particular, seismic methods, which provide the most direct definitive information, have the maximum potential for probing high temperature and partial melt in the Earth. Thus, from the standpoint of successful seismic exploration, an understanding of the seismic properties of rocks is an important requisite. The parameters of direct interest here are the seismic velocity and attenuation (Q^{-1}); the variables are pressure, temperature, frequency, fluid content, chemical composition (including volatile content), grain size and preferred mineral orientation.

It is anticipated that laboratory anelasticity data are valuable for the interpretation of seismic structure in terms of composition, temperature, and the degree of fluid or partial melt under regions where high attenuation (low Q) has been reported. The laboratory results are particularly applied to the locations of geophysical interest, the midocean ridge, the hot spot and the island arc, where seismic models have been extensively studied.

The recent progress in anelasticity study shows that the low Q asthenosphere beneath ocean basins is hot but solid, and that seismic wave absorption mostly occurs at the mineral grain boundaries. Partial melt exists only in the extremely low Q zones right beneath ocean ridges or hot spots. For island arc volcanism, the descending slab is thought to be a possible source of volatiles. A role of volatiles in arc volcanism will be investigated from laboratory Q studies on hydrous rocks.

Key words : low Q , grain boundary damping, grain size dependence, weak frequency dependence, volatile effect

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I. Introduction

In order to relate elasticity and anelasticity of the Earth as determined by seismologists to physical parameters such as temperature and degree of melt, the velocity and attenuation in rocks have been determined in the laboratory. Because of the technical difficulty, the pressure effect on the seismic properties of rocks has initially been ignored at high temperatures. In earlier studies, most seismic measurements were carried out as a function of temperature at one atmosphere (Woignard and Guéguen, 1978; Berckhemer *et al.*, 1982; Sacks and Murase, 1983; Kampfmann and Berckhemer, 1985; Sato and Manghnani, 1985; Manghnani *et al.*, 1986), or as a function of pressure at room temperature (Toksöz *et al.*, 1979; Katahara *et al.*, 1982; Jackson *et al.*, 1984; Carlson and Gangi, 1985). A small number of velocity measurements were made for mantle rocks at high pressure and relatively low temperatures (below 1000°C) compared to the upper mantle conditions (Spetzler *et al.*, 1969; Spetzler, 1970; Matsushima, 1972; Matsushima and Akeni, 1977; Fukizawa and Kinoshita, 1982).

Until recently, the studies by Murase and Kushiro (1979) and Murase and Fukuyama (1980), showing velocity drops as a function of melt fraction, were the only available data sources for velocities measured above the solidus of peridotites with high confining pressure (to 1 GPa). Anelastic properties of a peridotite were investigated, for the first time, by Sato *et al.* (1988a, b, 1989b) at high temperatures and 0.2–0.73 GPa confining pressures. These previous studies have measured velocity and attenuation at temperatures including both the sub- and hyper-solidus of the upper mantle rocks. Therefore, effects of partial melting on seismic properties were studied.

Their results indicate that partial melt does not produce any abrupt change in velocity and Q , rather elastic and anelastic properties of the upper mantle change gradually at the boundary where the geotherm crosses the solidus.

No frequency dependence of Q in peridotite was resolved from 60 to 880 kHz by Sato *et al.* (1989b), owing to the uncertainty in spectral ratio technique by means of analogue equipments in those days. A weak frequency dependence of seismic Q has been determined in the laboratory (e.g., Nur and Winkler, 1980; Kampfmann and Berckhemer, 1985; Jackson and Paterson, 1987; Jackson *et al.*, 1992, 2002; Gribb and Cooper, 1998) and in the Earth by seismic study (e.g., Sipkin and Jordan, 1979; Anderson and Given, 1982; Ulug and Berckhemer, 1984; Romero *et al.*, 1997; Haberland and Rietbrock, 2001; Gudmundsson *et al.*, 2004).

Sato *et al.* (1989b) pointed out that Q determined by means of an ultrasonic technique is comparable to seismic Q observed in the upper mantle. Their results indicate a wide distribution of relaxation frequencies in a peridotite, or higher relaxation frequencies due to smaller grain sizes in the laboratory than in the upper mantle. Their results have, therefore, noted that the study on the effects of grain size and frequency on Q in peridotite may reveal the mechanism of seismic wave absorption in the upper mantle. This study would also allow the extrapolation of the laboratory data to larger grain sizes found in the upper mantle. Until recently, effects of grain size on seismic measurements have not been investigated at high pressure and temperature. At one atmosphere and high temperature, Kampfmann and Berckhemer (1985) determined Q in gabbro of various grain size (0.25–

1 mm). In their study, however, a real grain-size dependence of Q may not be separated from the effect of cracks on Q , since the high pressure, to close cracks, is not applied to the sample. Lately, Tan *et al.* (2001) and Jackson *et al.* (2002, 2004) studied Q as a function of grain size and frequency at high pressure and temperature.

Here I briefly review the recent progress and the future perspectives of the laboratory anelasticity studies. A comprehensive review of seismic measurements and temperature estimates for low velocity and low Q zones studied before the mid 1990's was given by Sato (1995). Experimental techniques and results of rock anelasticity measurements have been reviewed by Jackson (1993, 2000).

II. Attenuation Mechanism

Influence of partial melting on seismic properties of rocks has been a fundamental problem in the Earth sciences. The model of partially molten upper mantle has long been discussed as the cause of the asthenosphere. However, a real mechanism of seismic wave absorption in the asthenosphere was not well known. Previous studies have shown the importance of partial melting, viscous grain boundary and dislocation motion for the attenuation (Jackson and Anderson, 1970; Guéguen and Mercier, 1973). A mechanism involving dislocations (Woignard and Guéguen, 1978; Minster and Anderson, 1980; Anderson and Minster, 1981; Guéguen *et al.*, 1981) or grain boundaries (Jackson, 1969; Goetze, 1977; O'Connell and Budiansky, 1977) has been proposed as a possible explanation for the low Q asthenosphere. If the relaxation frequency is observed within the frequency range of the laboratory measurement, this observation strongly constrains the mechanism of the at-

tenuation. For this purpose, laboratory studies should cover as wide frequency as possible.

Karato and Spetzler (1990) pointed out that dislocation and/or grain boundary mechanisms can have a significant effect on seismic wave propagation. Since the dislocation density and the grain size reflect the long-term tectonic stress, seismic wave attenuation and velocity dispersion are likely to depend on the magnitude of the tectonic stress as well as the temperature. In most experimental studies before 1990, however, the dislocation density or the grain size was not well controlled, making it difficult to identify the attenuation mechanism and preventing any quantitative applications to the Earth. The need for better characterization of defect microstructures in experimental study is emphasized by Karato and Spetzler (1990).

Jackson and Paterson (1987) measured shear modulus and internal friction of calcite rocks in the frequency range of 0.0033 to 1 Hz at 0–300 MPa. They observed that increase in pressure to about 100 MPa results in a marked increase in shear modulus and decrease in internal friction, indicating the closure of crack porosity. At higher pressures, shear modulus is much less pressure-sensitive and internal friction is pressure-independent with values less than 0.001. Within the pressure-independent regime, internal friction is also independent of frequency, and increases by only 30% as the grain size decreases from 1 mm to 4 μm . It is therefore concluded that internal friction of calcite rocks results from an intracrystalline mechanism involving dislocation damping with a broad range of relaxation times.

Jackson *et al.* (1992) measured anelasticity of Åheim dunite to 1000°C and 300 MPa over a seismic frequency range from 0.01 to

1 Hz and a low strain amplitude from 10^{-8} to 10^{-6} . At 300 MPa and 1000°C, up to 5% dispersion of the shear modulus and strong internal friction varying with frequency as $f^{-1/6}$ are observed. The energy dissipation appears to be concentrated within the olivine grains, indicating that intragranular anelastic relaxation in ultramafic rocks gives rise to losses comparable with those observed seismologically in the Earth's upper mantle. Their specimen shows strong anelastic relaxation under subsolidus conditions. The results suggest that it is not necessary to invoke the presence of melt to explain the low shear wave velocities and intense attenuation commonly observed in the upper mantle asthenosphere.

Sato *et al.* (1989b) proposed the model of grain boundary damping as the cause of the high attenuation in the upper mantle. They suggest that attenuation in peridotite can be controlled by grain boundary relaxation as described by Ke (1947, 1949) and Mosher *et al.* (1976). According to Ke (1947), relaxation frequency of Q is inversely proportional to the grain size. Therefore, it was pointed out that the study on the grain-size dependence of Q may be used to constrain attenuation mechanism in peridotite.

Many recent studies adopt absorption mechanisms activated at the grain boundaries (e.g., Gribb and Cooper, 1998; Tan *et al.*, 2001; Jackson *et al.*, 2002; Faul *et al.*, 2004). Those studies used fine-grained synthetic aggregates for elastic, anelastic and viscoelastic property measurements, because fine grains have the advantages of chemical homogeneity, controlled purity and microstructure, and resistance to thermal cracking (Jackson, 2000). Jackson (2000) reported that iron alloy, olivine and CaTiO₃-perovskite polycrystals show increases of dissipation and associated shear modulus

dispersion with increasing temperature and decreasing frequency, due to the loss of seismic energy at the grain boundaries.

Attenuation in a fine-grained olivine aggregate was first studied in torsion at high temperature and seismic frequency by Gribb and Cooper (1998). They argued that Andrade creep function fits to the creep and attenuation behavior of the olivine polycrystal, having the modest frequency dependence of Q as $Q \propto f^{0.35}$. Diffusional processes at the grain boundaries are suggested for absorption mechanism in their olivine and in the upper mantle.

Q in fine-grained polycrystalline olivine was further studied to 1300 °C at 200 MPa and seismic frequency by Tan *et al.* (2001). Their hot-pressed samples (less than 2 % porosity) were first annealed at 1300 °C for 7–47 hours, and measurements were carried out at successive cooling from 1300 °C to room temperature. Both shear modulus and Q in olivine increased with increasing annealing time, and eventually shear modulus approached the modulus of single crystal olivine. Their high-temperature results are expressed as $Q \propto A d^m f^\alpha \exp(\alpha E/RT)$, with $\alpha = 0.22 - 0.31$, $E = 410 - 508$ kJ/mol and $m = 0 - 0.5$ for 8–150 μm grain size, where d is grain size, f is frequency, E is activation energy, R is gas constant, T is temperature, and A , m and α are constant. Therefore, Q is grain-size sensitive, and grain-boundary sliding is suggested for the cause of anelastic and viscoelastic properties of the polycrystalline olivine.

Further, shear attenuations in four olivine polycrystals ranging in mean grain-size from 3 to 23 μm were extensively studied by Jackson *et al.* (2002). At 1000–1300°C, 0.01–1 Hz and 200 MPa, Q is expressed as $Q = A [d f \exp(E/RT)]^\alpha$, where α is 0.26 and E is 424 kJ/

mol. Extrapolations of their subsolidus results to upper mantle conditions give Q values comparable to seismic observations. Therefore, much of seismic wave attenuation in the asthenosphere (excluding right beneath the ridges) is attributed to grain boundary sliding in the absence of melt.

III. Effect of Partial Melt and Grain Size

By studying the variation of Q with melt fraction, frequency, temperature and grain size in olivine-basalt melt system, Jackson *et al.* (2004) observed a broad absorption peak, that was not detected in melt-free olivine polycrystals in the same frequency, temperature and grain-size range. The broad peak was a robust feature even for a small melt fraction (0.4%). Attenuation mechanism causing the broad peak was investigated by Faul *et al.* (2004). Their examinations of olivine-olivine grain boundaries by SEM, TEM and EDS and estimates of relaxation frequencies indicate grain-boundary sliding, not melt, as the cause of the attenuation peak. They note that the observed relaxation frequencies (~ 1 Hz) differ in several orders of magnitude from those of melt squirt model described by Mavko and Nur (1975). Extrapolations of their laboratory results to upper mantle grain sizes indicate that the broad peak may be responsible for nearly frequency independent attenuation in partially molten regions of the upper mantle. The extrapolations also suggest low melt fractions (0.1%) in average through relatively large regions (> 200 km horizontally) for Q models beneath hotspots and ridges, that may include both partially molten and melt-free mantle. The idea of small amount of melt is consistent with the melt fraction estimated by Sato and Sacks (1989, 1990) and Sato *et al.* (1989a, 1998, 2003), showing that zones of

partial melting are localized in the asthenosphere right beneath the ocean ridges.

Further, mantle seismic structures are compared with velocity and attenuation in olivine aggregates measured as a function of temperature and grain size by Faul and Jackson (2005), to study variations of temperature and grain size in the upper mantle. The comparison of laboratory data by Tan *et al.* (2001) and Jackson *et al.* (2002) with seismic models again indicates the low velocity and low Q zones beneath oceans to be subsolidus high-temperature (no melt) regions. While relatively large velocity variations in the upper mantle (< 200 km depth) are explained by temperature differences, the velocity increase at > 200 km depth indicates an increase in grain size from order of mm to cm (Faul and Jackson, 2005).

IV. Future Perspectives

Laboratory anelasticity measurements are scarce, and too little to constrain the attenuation mechanism and the mechanical properties of the Earth. Further investigations are necessary to allow the comparison of laboratory results with field seismic data. The previous attenuation measurements on, e.g., mantle rocks are limited for dry peridotites or synthetic olivine polycrystals. No systematic laboratory investigations are ever made for the effects of volatiles (H_2O and/or CO_2) on seismic properties at high pressure and temperature. The solidus temperatures of rocks are largely reduced by the presence of volatiles (e.g., Kushiro *et al.*, 1968; Millhollen *et al.*, 1974; Ringwood, 1975; Wyllie, 1979; Thompson, 1992; Schmidt and Poli, 1998; Litasov and Ohtani, 2002; Kawamoto, 2004). Seismic properties of rocks may strongly depend on volatile contents. It is interesting to study if

Q -homologous temperature relation observed in dry peridotite by Sato *et al.* (1989b) will also be confirmed in hydrous peridotite. A role of volatiles in the Earth needs to be investigated from laboratory and seismic Q data.

The torsion technique as developed by Australian National University group is a powerful tool to study shear velocity (V_s) and attenuation (Q_s^{-1}) at seismic frequencies (e.g., Jackson, 2000). However, the technique does not allow one to determine P-wave properties (V_p and Q_p), and is currently limited to relatively low pressure range (< 0.3 GPa).

At higher pressures to 0.6 GPa by means of ultrasonic techniques, Kern at University of Kiel, Germany and his colleagues measured Q_p and Q_s as well as V_p and V_s simultaneously in serpentinite and amphibolite (Kern *et al.*, 1997), and in granite, graywacke and sandstone (Liu *et al.*, 1997). Kern *et al.* (1997) also reported S-wave splitting along the three orthogonal directions of the cubic samples at pressures to 0.6 GPa and temperatures to 700 °C. Therefore, they reported nine velocity and nine attenuation data, that is, velocity anisotropy, Q anisotropy, acoustic birefringence, V_p/V_s ratio and Q_p/Q_s ratio; all of them corresponding to seismic properties of one single rock sample. Velocity anisotropy that is caused by both the oriented microcracks and the lattice preferred orientation of antigorite or hornblende decreases with increasing pressure owing to the closure of microcracks (Kern *et al.*, 1997). On the other hand, anisotropy of Q in serpentinite and amphibolite is low at low pressure and enhanced as pressure is increased. At high pressure, Q_p is highest in the direction normal to the foliation plane, whereas V_p and V_s are generally lowest in the same direction. Closure of oriented microcracks and increase of contact areas in be-

tween the grain boundaries along the foliation are suggested for the reason of the highest Q_p (Kern *et al.*, 1997). Anisotropy increase in Q_p at high pressure is observed in their study, and attributed to a directional dependent decrease of open cracks.

A full understanding of rock anelasticity has to await further laboratory measurements at the conditions of the upper mantle (above 1 GPa and high temperature). Recently, Sato *et al.* (2004) have developed the method of simultaneous velocity and attenuation measurements at high pressure and temperature. By observing both the direct and reflected echoes, pulse overlap and spectral ratio techniques are conveniently used to determine intrinsic sample properties and to eliminate unknown extrinsic effects, such as buffer rod properties, assembly geometries and frequency characteristics of transducers and instruments being common to both echoes (Sato *et al.*, 2004). In situ measurements of travel time and spectral amplitude of echoes transmitted only within the sample are essential for determining accurate velocity and attenuation simultaneously at high pressure and temperature. The high acoustic impedance of platinum is suitable as a buffer rod for observing both the direct and reflected echoes, and so for determining intrinsic properties, of various samples of ceramics, minerals, glasses and light metals. By using platinum rods, Sato *et al.* (2004) determined compressional-wave velocity and attenuation in fused silica at 1 GPa and temperatures to 1200 °C. Their measured velocities were consistent with the values reported earlier. In general, the acoustic impedance of platinum is much higher than that of ceramics, minerals, rocks, glasses and light metals. Therefore, their method should be applicable to velocity and attenuation measurements for various sol-

ids at high pressures and temperatures. Velocity and Q measurements at pressures to 3 GPa and temperatures to 1300°C are currently underway by Sato *et al.* (2005).

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高温高压における岩石の非弾性研究

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地球内部温度構造を調べる地球物理学的手法に、地殻熱流量の測定や地震学的手法、また電磁気学的な観測手法がある。これら物理探査の目的は観測量の異常を検出し、また異常の原因を解明し、地球の熱モデルを構築することにある。とりわけ、地震学的手法は地球内部の高温と部分熔融量を見積もるのに最も強力な手段を提供するので、岩石の地震波速度と減衰係数 (Q^{-1}) を実験室にて高温高压下で決定したい。コントロールする変数は温度、圧力、周波数、化学組成、流体量、結晶粒径と鉱物の格子選択配向である。特に高減衰（低 Q ）が報告される海洋中央海嶺やホットスポット、

また島弧下の組成や温度、流体量を見積もる際に、実験室の非弾性データは大変有力な手段となる。

近年の地球内部構成物質に関する非弾性研究により、海洋下の低 Q アセノスフェアは一般に高温であるがメルトを含まず、地震波の減衰は主に鉱物結晶粒界で起きていることが明らかとなってきた。部分熔融は海嶺やホットスポット直下の顕著な低 Q 層にのみ存在する。また、島弧では沈み込むスラブが揮発性成分の供給源と考えられ、島弧火山活動における揮発性成分の役割について、今後、含水鉱物や含水岩石に関する Q 値の研究から明らかにする必要がある。

キーワード：低 Q ，粒界減衰，粒径依存性，弱い周波数依存性，揮発性成分の効果

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