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ROCK VELOCITIES AT ATMOSPHERIC PRESSURE AND ROOM TEMPERATURE IN TANZAWA PLUTONIC ROCKS FROM CENTRAL JAPAN

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Abstract: The Tanzawa plutonic complex, which is composed mainly of tonalite with minor quartz gabbro and gabbro, is exposed at the northern end of the Izu-Bonin island-arc. It is interpreted as exposed middle crust of the Izu-Bonin arc which was uplifted during the collision of Izu-Bonin arc with the Honshu arc in Japan. Determination of elastic wave velocity in these rocks is crucial to interpret the seismic velocity structure of the Izu-Bonin arc.

Compressional-wave (Vp) and shear-wave (Vs) velocities from Tanzawa plutonic rocks were measured at 1 atm and room temperature. The P-wave and S-wave velocities are strongly dependent upon the lithology: gabbro (Vp=4.89-5.44 km/s, Vs=2.49-2.86 km/s), quartz gabbro (Vp=4.90-4.97 km/s, Vs=2.39-2.50 km/s), tonalite (Vp=4.25-4.71 km/s, Vs=2.40-2.48 km/s), granitic aplite (Vp=3.82 km/s, Vs=2.11 km/s). The Tanzawa plutonic rocks show a positive correlation between elastic-wave velocity and density, and a rough positive correlation between Vp and Vs.

Theoretical Voigt-Reuss-Hill average Vp values were also calculated for tonalites, quartz gabbro and gabbros at 1.0 GPa pressure. Theoretical Vp is about 2 km/s faster than measured Vp at atmospheric pressure. The measured Vp of plutonic rocks (4.25-5.44 km/s) is faster than the refraction-determined P-wave velocity in 2 km-thick uppermost crust (2.5-4.0 km/s) of the Izu-Bonin island arc, implying that plutonic rocks are not present at 0-2 km depth. Theoretical Vp values of tonalite and quartz gabbro are consistent with the velocity structure of middle crust (6.0-6.7 km/s velocity). The theoretical Vp of hornblende gabbro (7.0-7.2 km/s) can explain the lower crustal P-wave velocity structure (7.1-7.2 km/s). The high P-wave velocity (7.2-7.3 km/s) in the lowermost crust implies a high content of orthopyroxene (more than 20%).

key words: compressional-wave, shear-wave, Poisson's ratio, acoustic impedance, island-arc

1. Introduction

The Izu-Bonin-Mariana arc system can be regarded as a natural laboratory for understanding crustal processes in a convergent plate margin between oceanic plates, as it is one of the simplest of all arc systems with a well-known geologic history and modern geodynamic setting. The Miocene Tanzawa plutonic complex, consisting mainly of tonalite intrusions, is exposed in central Japan where the northern end of the Izu-Bonin-

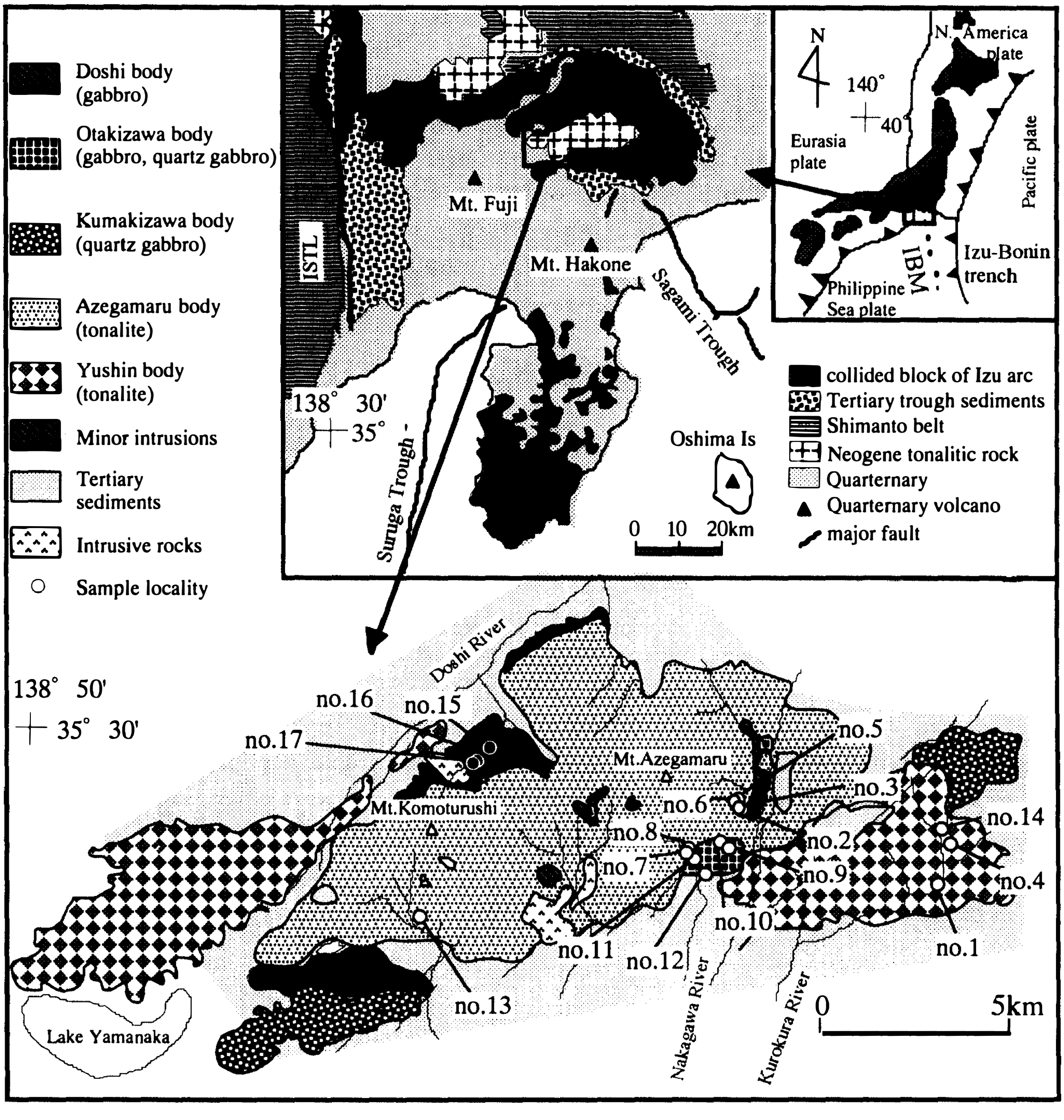

Fig. 1. Geological map of the Tanzawa Mountain Range, modified after Takita *(1974, 1980),* Sugiyama *(1976) and* Kawate *(1994). The Miocene Tanzawa plutonic complex is exposed in central Japan where the northern end of the Izu-Bonin-Mariana island (IBM) island arc collided with the Japan Honshu arc. The Tanzawa plutonic complex is interpreted as the middle crust of the Izu-Bonin arc, exposed during the arc-arc collision (*Taira *et al., 1992). The Tanzawa plutonic complex consists mainly of tonalitic bodies (Azegamaru, Yushin bodies) and minor mafic bodies (Otakizawa, Kumakizawa, Doshi bodies). Numbers show the locality of each sample listed in Table 1. ISTL: Itoigawa-Shizuoka Tectonic Line.*

Mariana island-arc collides with the Japan Honshu arc (Fig. 1). Results from most comprehensive seismic experiments on the northern Izu-Bonin arc (Suyehiro *et al.*, 1996) suggest the presence of felsic middle crust (6.0 km/s P-wave velocities) at a depth from 7 to 12 km, and mafic lower crust (7.1-7.3 km/s P-wave velocities). This seismic structure supports the tectonic model of Taira *et al.* (1992) in which the Tanzawa plutonic complex is interpreted as an exposed middle crust of the Izu-Bonin arc that was uplifted during the arc-arc collision.

Tanzawa plutonic rocks are petrologically well characterized (KAWATE, 1997) and, therefore, the determination of elastic wave velocities of Tanzawa plutonic rocks at atmospheric to lower crustal pressure is useful to interpret seismic sections of the Izu-Bonin arc crust in terms of petrological type. In order to construct a data base of seismic velocity in island arc crustal rocks, preliminary measurements of compressonal-wave (P-wave) and shear-wave (S-wave) velocities in the Tanzawa plutonic rocks were performed at 1 atm pressure prior to planned future high pressure measurements.

2. Sample Descriptions

The Tanzawa plutonic complex was classified into five distinct plutonic bodies, based on field criteria (TAKITA, 1974). According to KAWATE (1994), petrologic features of each body are as follows (see details in TAKITA, 1974, 1980; KAWATE, 1994): (1) The most voluminous lithologic type, the Azegamaru body, consists mainly of tonalite and shows a wide range of SiO_2 variation (55–70 wt%). It includes mafic enclaves in some places. (2) The second most voluminous body, the Yushin body, is composed of homogeneous tonalite and shows a relatively narrow range of SiO_2 content (70–72 wt%). Compared to Azegamaru tonalite, quartz content is relatively high (about 40%) in the Yushin tonalite. (3) The less voluminous bodies are characterized by relatively low SiO_2 (<60 wt%) content. The Kumakizawa body is comprised of quartz gabbro. The Otakizawa body is defined as an assemblage of many enclaves of gabbro and quartz gabbro in the Azagamaru tonalitic body. (4) The Doshi body is a gabbroic body.

Table 1. Densities, compressional-wave velocity (Vp), shaer-wave velosity (Vs), and mineral modes in Tanzawa plutonic rocks.

Sample no.	Rocks	Density g cm³	Measured Vp km s⁻¹	Measured Vs km s⁻¹	Calculated Vp km s⁻¹	Calculated Vs km s⁻¹	Qtz	Pl	Kfs	Pth	Hbl	Cum	Opx	Cpx	Bt	Chl	Opq	Body
							Modes of minerals (%)											
1	aplite	2.56	3.82	2.11			46	4	5	44	0	0	0	0	1	0	0	
2	tonalite*	2.63	2.74	1.59	6.58	3.79	20	67	0	0	3	0	0	0	6	2	2	Azegamaru
3	tonalite	2.66	4.71	2.48	6.67	3.94	26	63	0	0	7	1	3	0	0	0	0	Azegamaru
4	tonalite	2.70	4.25	2.40	6.56	3.97	38	49	0	0	6	0	4	0	1	2	0	Yushin
5	tonalite*	2.73	2.78	1.66	6.71	3.96	25	61	0	0	7	0	6	0	0	0	1	Azegamaru
6	tonalite*	2.72	3.00	1.89	6.72	3.98	21	59	0	0	12	0	3	0	0	1	4	Azegamaru
7	quartz gabbro	2.79	4.90	2.50	6.92	3.99	6	68	0	0	17	1	0	4	0	3	1	Otaki
8	quartz gabbro	2.81	4.97	2.39	6.85	4.00	10	60	0	0	18	3	0	0	1	2	6	Otaki
9	quartz gabbro⁺	2.83	4.31	2.24	7.00	3.94	8	59	0	0	18	2	0	0	5	3	5	Otaki
10	quartz gabbro⁺	2.81	3.94	2.24	7.03	4.04	5	61	0	0	21	1	0	3	0	2	7	Otaki
11	gabbro*	2.86	4.30	2.39	7.03	3.97	0	68	0	0	18	2	0	7	2	0	3	Otaki
12	gabbro	2.89	5.39	2.62	7.00	3.96	0	64	0	0	18	5	0	5	3	0	5	Otaki
13	gabbro	2.90	5.02	2.68	7.08	4.02	0	64	0	0	19	5	1	5	0	0	6	
14	gabbro	2.95	5.44	2.77	7.09	4.03	0	65	0	0	18	2	3	7	0	2	3	
15	gabbro	2.94	5.25	2.86	7.14	4.07	0	63	0	0	17	1	10	4	0	0	5	Doshi
16	gabbro	2.93	4.89	2.49	7.12	4.06	0	66	0	0	19	1	8	2	0	0	4	Doshi
17	gabbro*	2.89	4.37	2.52	7.16	4.07	0	66	0	0	16	1	13	3	0	0	1	Doshi

Abbreviation ; Qtz = quartz, Pl = plagioclase, Kfs = K-feldsper, Pth = perthite, Hbl = hornblende, Cum = cummingtonite, Opx = orthopyroxene, Cpx = clinopyroxene, Bt = biotite, Chl = chlorite, Opq = opaque,* : altered rock. #: cracked rock, + : sheared rock.

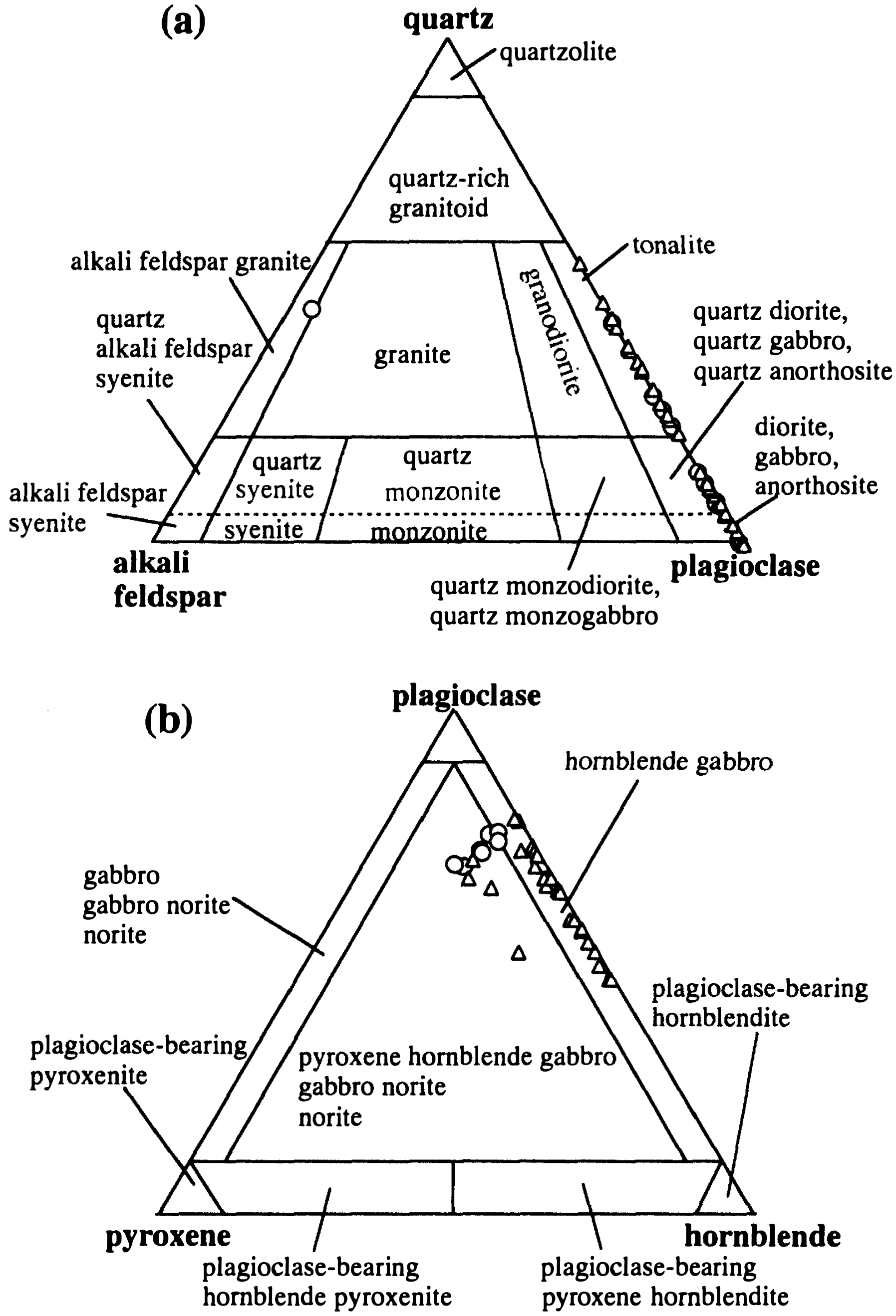

Fig. 2. Triangle compositional diagrams: (a) tonalite, quartz gabbro, and (b) gabbro from the Tanzawa plutonic complex. The results (open circles) of the modal analysis are given as volume percentages of major minerals in Table 1. In addition, modal compositions of K*AWATE and* A*RIMA (1998) are also plotted on the diagrams (open triangles). Note that the plutonic rocks can be divided into three main categories: tonalite, quartz gabbro and gabbro.*

Rock samples used here were collected from the Tanzawa Mountain Range (see Fig. 1 for sample locations). The specimens represent a wide variety of felsic to mafic plutonic rocks. Modal analyses of each sample were performed using the standard thin section point counting method. One hundred points were counted on one thin section from each sample. The plutonic rocks can be divided into four categories: tonalite, quartz gabbro, gabbro and aplite. The results of the modal analysis are given as volume percentages of major minerals in Table 1 and Fig. 2.

Tonalite is the predominant rock type in the Tanzawa Complex. It is commonly massive and generally medium to coarse-grained (2–3 mm). Quartz gabbro is massive and medium to coarse-grained (2–4 mm). Quartz gabbro occurs as mylonitic rock near the southern end of the Azegamaru-type tonalite body, and the specimens show a strong foliation and a lineation defined by the hornblende alignment. Gabbro samples were collected from the Doshi body, and from enclaves of 50 cm diameter in tonalite. They are massive and medium to coarse-grained (2–3 mm). Most of the gabbro samples are plotted as hornblende gabbro in the compositional diagrams (Fig. 2). Aplite occurs as only a few veins less than 10 cm thick within the tonalite body. The main constituents are quartz and perthite, and thus the rock is classified as an alkali feldspar granite.

3. Experimental Approach

The compressional-wave velocity (Vp) and shear-wave velocity (Vs) were determined by measuring the travel time of an ultrasonic wave through a rock specimen of known length at room temperature and 1 atm. The laboratory instrument for velocity measurement, a Sonic-Viewer 170 (Oyo Corporation), generates ultrasonic compressiona-wave and shear-wave pulses and measures travel times of ultrasonic pulses through the rock samples. The transmitter and receiver cover both ends of the specimen, which are about 5.0 cm long. Compressional-wave and shear-wave pulses are generated by 63 kHz or 33 kHz transducers, transmitted through the specimen, and an electrical signal converted from the elastic wave is amplified and displayed on a digital oscilloscope. The travel time through the specimen is quickly obtained on the digital oscilloscope from the time gap between the travel times for the transmitter-specimen-receiver and the transmitter-receiver.

The rock specimens were first cut and ground to cubes of about 40–70 mm in length. Vp and Vs were measured in three orthogonal directions. The directions are arbitrary because the Tanzawa plutonic rocks exhibited no fabric elements on a hand specimen-scale (except for mylonites). These sample cubes were oven-dried for twenty four hours to minimize the effect of the pore fluid on velocity measurements.

Sampling rates of signals in the digital oscilloscope are 0.1 ns/sample in the Vp measurements and 0.2 ns/sample in the Vs measurements. Errors in specimen length are less than 0.5 mm. Consequently, the errors in the Vp and Vs measurements are in the range from -0.01 to $+0.10$ km/s and from -0.01 to $+0.05$ km/s respectively. Velocity data are summarized in Table 1.

4. Results

Vp and Vs are strongly dependent upon the lithology of the Tanzawa plutonic rocks. Gabbros are characterized by high velocities ($Vp=4.89$–5.44 km/s, $Vs=2.49$–2.86 km/s). Quartz gabbros exhibit intermediate velocities ($Vp=4.90$–4.97 km/s, $Vs=2.39$–2.50 km/s). Tonalites have in general relatively low velocities ($Vp=4.25$–4.71 km/s, $Vs=2.40$–2.48 km/s). The lowest velocities are measured in the aplite specimen ($Vp=3.82$ km/s, $Vs=$

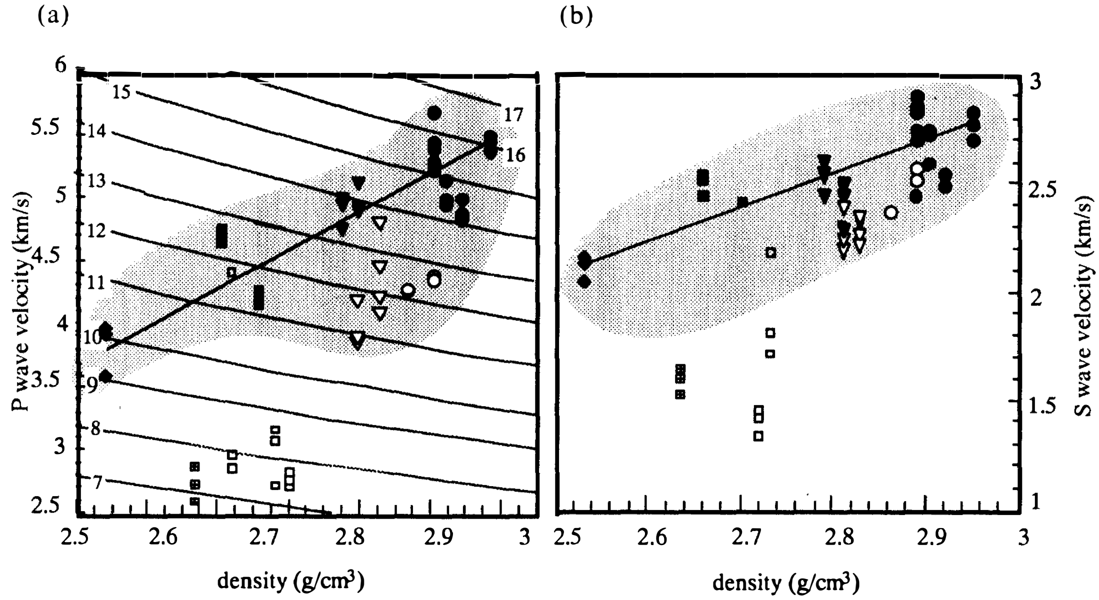

Fig. 3. Rock velocity versus density: (a) P-wave, (b) S-wave. The unaltered, uncracked rocks demonstrate positive correlation between velocity and density. The solid lines represent velocity versus density lines calculated by the method of least squares. Also shown are curves of acoustic impedance ($10^6 kg/m^2s$). Solid circles: gabbro, open circles: cracked gabbro, solid triangles: quartz gabbro, open triangles: sheared quartz gabbro, solid squares: tonalite, open squares: altered tonalite, crossed squares: cracked tonalite.

2.11 km/s) Figure 3 displays plots of *Vp* and *Vs* versus density. The solid symbols show uncracked and unaltered specimens, and open symbols denote cracked or altered specimens (see Table 1) The unaltered, uncracked rocks show positive correlation between velocity and density. The solid lines give velocity versus density, calculated by the method of least squares. On the other hand, altered and cracked rocks have their own correlation between velocity versus density. Compared to unaltered and uncracked rocks, *Vp* values of these rocks are 1.5 km/s lower than those of unaltered, uncracked specimens, and *Vs* values of these rocks are 1.0 km/s lower than those of unaltered, uncracked specimens.

In general, it is apparent that different rock types do not have unique *Vp*. There are some overlaps among the velocities of tonalite, quartz gabbro, and gabbro. Tonalites overlap with quartz gabbro, and the latter overlap gabbros. Our analysis suggests that each lithology has a distinctive acoustic impedance (the product of *Vp* and density) cluster. Acoustic impedances for aplite, tonalite, quartz gabbro, and gabbro are about 9.0-10.1 $\times 10^6$ kg m^{-2} s^{-1}, 11.2-12.6 $\times 10^6$ kg m^{-2} s^{-1}, 13.1-14.4 $\times 10^6$ kg m^{-2} s^{-1}, and 14.0-16.5 $\times 10^6$ kg m^{-2} s^{-1}, respectively (Fig. 3a).

A schematic view of the variation of *Vp* and *Vs* is presented as histograms in Fig. 4 where each column represents one specimen. It is clear from the diagram that velocities are closely related to the percentages of major minerals in rocks and the respective single crystal velocities. In general, high contents of pyroxene and amphibole produce high *Vp* and *Vs*. On the other hand, increasing quartz content results in a decrease of *Vp* and *Vs*. For example, sample no. 4 has relatively low *Vp* and *Vs* compared to no. 3 and no. 7. In other words, an increase in the amount of high-density minerals, *e.g*. pyroxene and

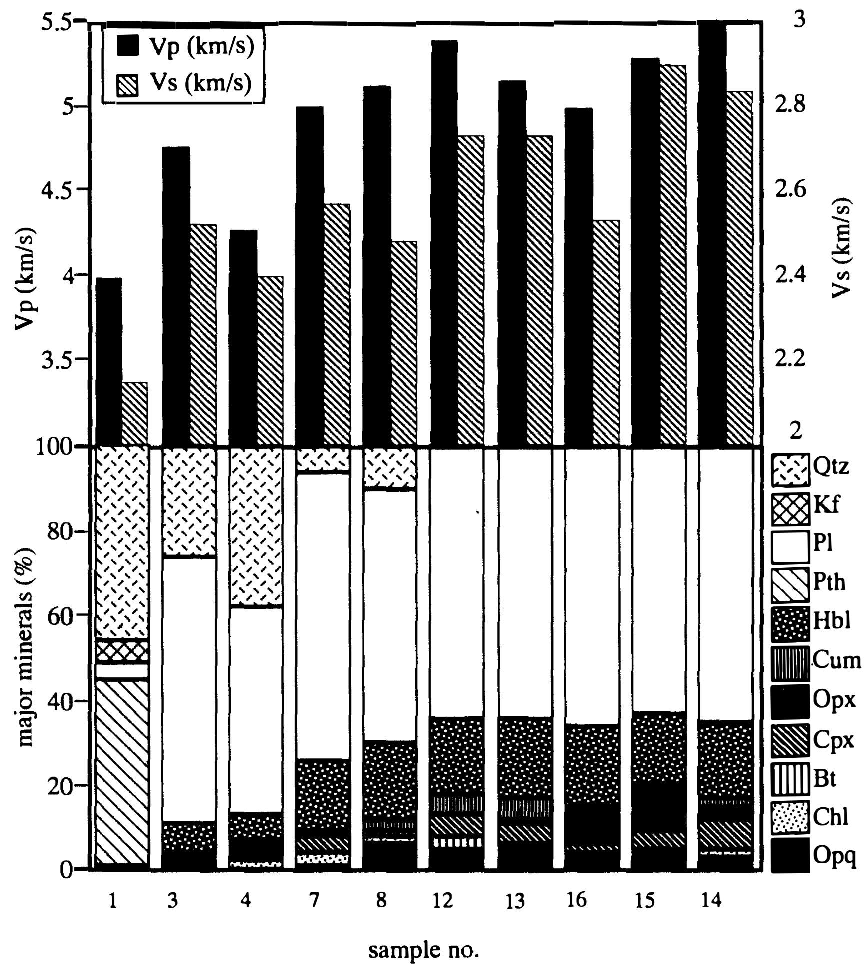

Fig. 4. Comparison between modal percentages of major minerals and Vp, Vs. Note that high contents of pyroxene and amphibole produce fast Vp and Vs, whereas increasing quartz content results in slow Vp and Vs.

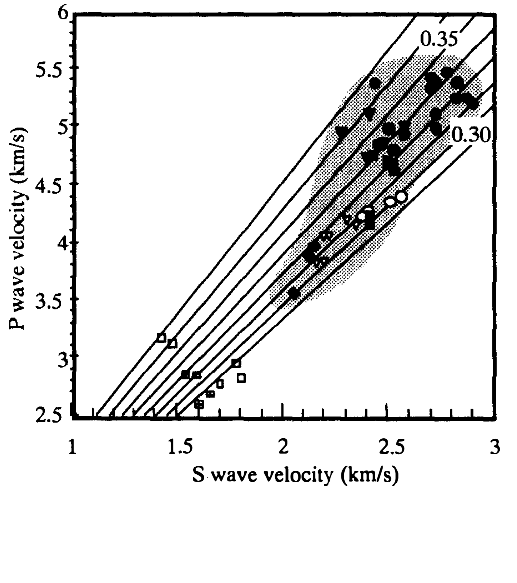

Fig. 5. P-wave velocity versus S-wave velocity. Lines of constant Poisson's ratio are superimposed (symbol: see Fig. 3). Note that most of the unaltered and uncracked rocks lie between Poisson's ratio lines of 0.30 and 0.35, and there is a trend relating Poisson's ratio to composition for plutonic rocks.

amphibole, gives high velocities, and an increase in the low-density mineral (*e.g.* quartz) content gives low velocities.

Vp is plotted versus *Vs* in Fig. 5. Also shown in Fig. 5 are lines of constant Poisson's ratios. Most of the unaltered and uncracked rocks are plotted between Poisson's ratios of 0.30 and 0.35, which are high values compared to measurements at high pressure. Poisson's ratio is related to the composition of plutonic rocks. Poisson's ratios of aplitic granite are relatively low (0.30–0.32). Poisson's ratio increases to 0.33 for tonalite and to 0.33–0.36 for quartz gabbro and gabbro. A similar trend is reported in high pressure studies (*i.e.* CHRISTENSEN, 1996), but the Poisson's ratios at room pressure are 0.05 lower than those at high pressure. Poisson's ratios of cracked and altered rocks are highly variable because of wide ranges in *Vp* and *Vs* for altered and cracked rocks.

5. Discussion

Compositional diagrams show theoretical Voigt-Reuss-Hill average *Vp* in km/s for tonalite, quartz gabbro and gabbro at 1.0 GPa pressure (Fig. 6). The calculations are based on the average *Vp* of a single crystal (ANDERSON *et al.*, 1968; SIMMONS and WANG, 1971; BIRCH, 1961).

Compared to the Voigt-Reuss-Hill average *Vp* at 1.0 GPa, the *Vp* of uncracked/unalterd rocks measured at atmospheric pressure is about 2 km/s slower. However, the measured *Vp* values of plutonic rocks (4.25–5.44 km/s) are faster than *Vp* in the uppermost crust (2.5–4.0 km/s) of the Izu-Bonin island arc (SUYEHIRO *et al.*, 1996), which probably implies that plutonic rocks are not present at 0–2 km depth.

The theoretical *Vp* values of tonalite and quartz gabbro range widely from 6.3 to 7.0 km/s because of wide variations of modal composition and anorthite content in plagioclase (plagioclase in Tanzawa tonalites has a wide range of anorthite content (10–90%) (KAWATE and ARIMA, 1998). Because the average *Vp* of a single crystal of plagioclase is strongly dependent upon the anorthite content (An), *Vp* in tonalite with An_{10} plagioclase is 0.2–0.3 km/s slower than *Vp* in tonalite with An_{90} plagioclase (BIRCH, 1961).

Vp values under midcrustal pressure-temperature conditions are about 0.2–0.3 km/s slower than velocities under 1.0 GPa and room temperature conditions (KERN, 1982a, b). Therefore, the theoretical *Vp* of tonalite and quartz gabbro is in good agreement with 6.0–6.7 km/s *Vp* (SUYEHIRO *et al.*, 1996) in the middle crust.

On the other hand, it is difficult to explain 7.2–7.3 km/s in the lowermost crust (SUYEHIRO *et al.*, 1996) by any Tanzawa rock type *e.g.* hornblende gabbro (theoretical $Vp = 7.0$–7.2 km/s). Theoretical calculations require higher pyroxene content (more than 20%) in the lowermost crust to explain 7.2–7.3 km/s velocity. This is consistent with the petrological constraint from melting experiments (NAKAJIMA and ARIMA, 1998), that indicate that the principal lower crustal component of Izu arcs is pyroxene-rich norite.

6. Conclusions

We draw the following conclusions from the velocity measurements in uncracked and unaltered rocks from the Tanzawa plutonic complex: (1) The *Vp* and *Vs* are strongly dependent upon lithologies: $Vp = 4.89$–5.44 km/s, $Vs = 2.49$–2.86 km/s for gabbro, $Vp =$

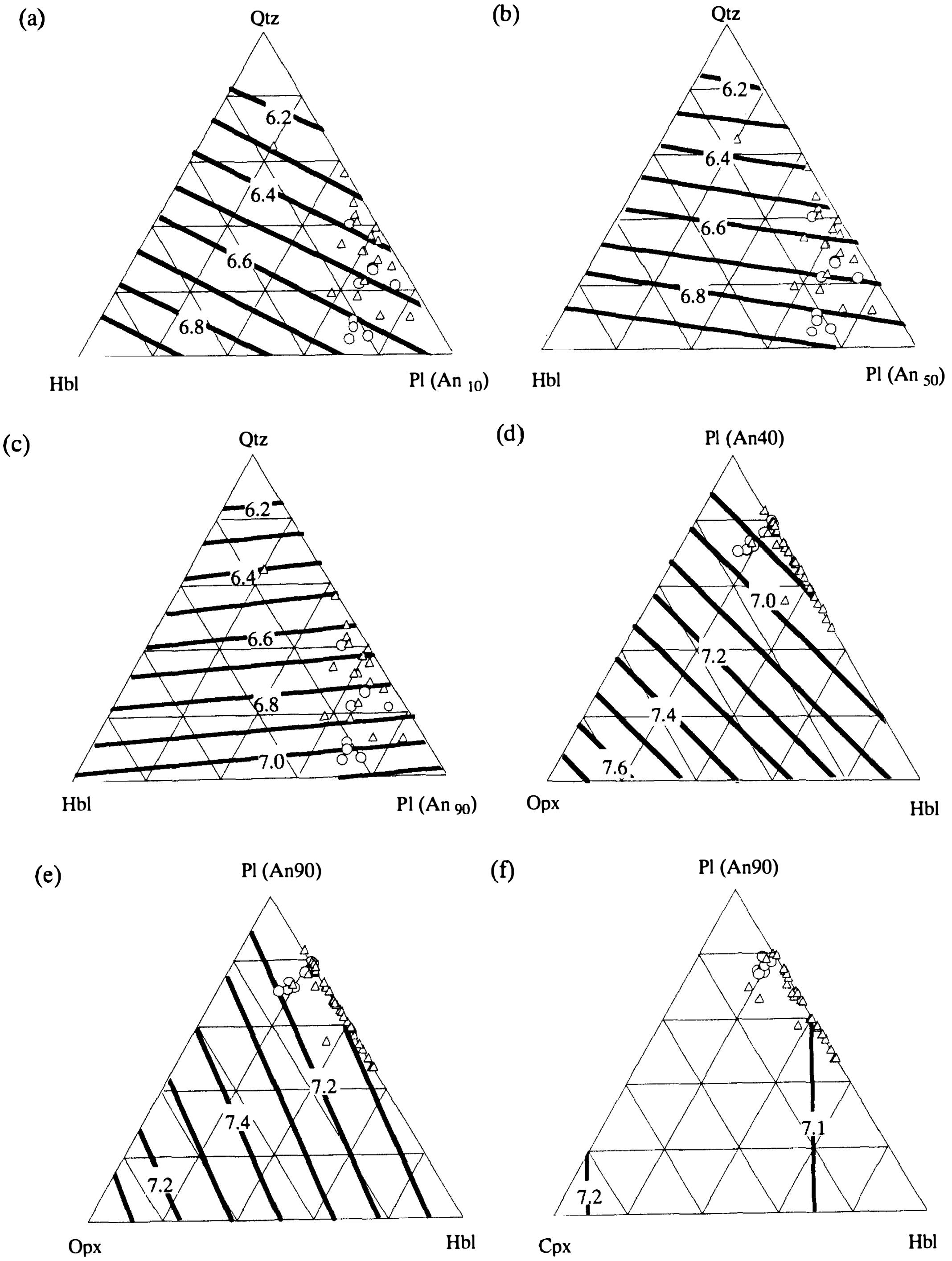

Fig. 6. Theoretical compressional-wave velocity calculated from the Voigt-Reuss-Hill single crystal average at 1.0 GPa pressure. Compositional diagrams show theoretical Voigt-Reuss-Hill average Vp in km/s for tonalite, quartz gabbro (a, b, c), and compositional diagrams for gabbro (d, e, f). Qtz: quartz: Pl (An_{90}): plagioclase as 90% anorthite content; Hbl: hornblende; Opx: orthopyroxene; Cpx: clinopyroxene. Open circles are given as volume percentages of major minerals in Table 1. In addition, modal compositions of KAWATE *and* ARIMA *(1998) are also plotted on the diagrams (open triangles). Averaged Vp values of single crystals are based on previous studies: Opx and Qtz data from* ANDERSON *et al. (1968), Cpx and Hbl data from* SIMMONS *and* WANG *(1971), and Pl data from* BIRCH *(1961).*

4.90-4.97 km/s, $Vs=2.39$-2.50 km/s for quartz gabbro, $Vp=4.25$-4.71 km/s, $Vs=2.40$-2.48 km/s for tonalites, $Vp=3.82$ km/s, $Vs=2.11$ km/s for granitic aplite. (2) Vp and Vs are controlled by modal minerals. Rocks with high pyroxene and amphibole content show high elastic wave velocities, whereas elastic wave velocities decrease with increasing quartz content. (3) Tanzawa plutonic rocks have a positive correlation between elastic wave velocity and density. (4) Tanzawa plutonic rocks exhibit rough positive correlation between the compressional-wave and shear-wave velocities. Most unaltered and uncracked rocks plot between Poisson's ratios lines of 0.30-0.35; 0.3-0.32 for aplite, 0.33 for tonalite, 0.33-0.36 for quartz gabbro and gabbro.

The conclusions from the velocity measurements for cracked or altered rocks are as follows: (1) Cracks and alteration have a strong influence on Vp and Vs and cause the reduction of velocities and acoustic impedances. (2) Poisson's ratios of cracked and altered rocks are highly variable, however, the cluster of cracked and altered rocks is separate from that of uncracked/unaltered rocks.

Theoretical Voigt-Reuss-Hill average Vp values in km/s for tonalite, quartz gabbro and gabbro at 1.0 GPa pressure indicate the following: (1) Compared to the Voigt-Reuss-Hill average Vp at 1.0 GPa, the Vp of uncracked/unalterd rocks measured at atmospheric pressure is about 2 km/s slow. (2) The measured Vp of plutonic rocks (4.25-5.44 km/s) is faster than Vp in the uppermost crust (2.5-4.0 km/s) of the Izu-Bonin island arc, which probably implies that the plutonic rocks are not present at 0-2 km depth. (3) The theoretical Vp in tonalite and quartz gabbro (6.3-7.0 km/s) is consistent with seismic data in the middle crust (6.0-6.7 km/s velocity) when pressure and temperature derivatives are considered. (4) The theoretical Vp of hornblende gabbro (7.0-7.2 km/s) can explain the 7.1-7.2 km/s velocity in the lower crust. (5) High velocity (7.2-7.3 km/s) means higher orthopyroxene (more than 20%) content in lowermost crust of the Izu-Bonin island arc.

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