LABORATORY MEASUREMENTS OF ULTRASONIC VELOCITIES ON CORE SAMPLES FROM THE AWIBENGKOK GEOTHERMAL FIELD, INDONESIA

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BACKGROUND

The Awi 1-2 corehole has provided 1.1 km of continuous core from the Awibengkok geothermal field in Indonesia. The core is representative of volcanic hosted hydrothermal systems which are important to the geothermal industry. A collaborative research effort has been initiated to study this core (see Hulen and Anderson, 1998). As part of the effort, this work has concentrated on making laboratory measurements on a representative set of core samples in order to develop a better understanding of the interrelationships between physical properties and petrographic characteristics. In this paper, we report on the results of ultrasonic velocities measured as a function of effective confining pressure and saturation. Results are compared with similar measurements on core samples from The Geysers geothermal field, illustrating some common characteristics among the cores from these very different geothermal fields.

General Observations

The Awi 1-2 core contains a wide variety of rock types, including hydrothermally altered lahars, tuffs, and dacitic and andesitic flow units. A thick microdiorite intrusive is also present. Sampling for this study has concentrated on the dominant lahars and flow units. Three dacite autobreccias, five andesites, and nine lahars were selected, spanning depths from 768 m to 1819 m. One sample of the microdorite intrusive and one tuff sample were also selected. From these samples, a number of plugs were prepared for testing. Samples characteristics and dry velocities are tabulated in Table 1.

Table 1. Sample Characteristics and Dry Velocities for Selected Cores †

Plug -	Depth m	Lithology -	Dry Density kg/m^3	Porosity -	V_p m/s	V_s m/s	V_p/V_s -
2520_0a	768.10	Lahar	2339	0.144	4322	2700	1.60
2541_7a	774.71	Lahar	2185	0.186	4429	2676	1.66
2541_8a	774.74	Lahar	2259	-	4494	2676	1.64
2845_7a	867.37	Mixed Lithology	2384	-	5314	3436	1.55
3035_0a	925.07	Dacite Autobreccia	2313	0.116	4173	2643	1.58
3052_3a	930.34	Dacite Autobreccia	2298	-	4132	2575	1.60
3100_1a	944.91	Dacite Autobreccia	2293	0.138	3960	2520	1.57
4072_7a	1241.36	Lahar	2419	0.122	4728	2871	1.65
4125_3a	1257.39	Lahar	2461	0.103	4922	2999	1.64
4218_0a	1285.65	Lahar	2450	0.108	4771	2854	1.67
4290_3a	1307.68	Lahar	2444	0.118	4821	2881	1.67
4504_4a	1372.94	Andesite	2705	0.062	5263	3111	1.69
4789_0a	1459.69	Andesite	2406	0.126	4828	2869	1.68
5091_1a	1551.77	Lahar	2156	0.172	4428	2627	1.69
5110_2a	1557.59	Andesite	2464	-	4520	2836	1.59
5503_0a	1677.31	Lahar	2648	0.052	4844	2911	1.66
5513_6a	1680.55	Lahar	2463	0.132	5090	3077	1.65
5676_4a	1730.17	Microdiorite	2696	-	5385	3120	1.73
5705_6a	1739.04	Unspecified	2231	-	4434	2544	1.74
5868_7a	1788.78	Andesite	2784	-	6200	3352	1.85
5890_0a	1795.27	Andesite	2607	-	4384	2810	1.56
5967_2a	1818.80	Tuff	2342	-	4157	2641	1.57

† Velocities measured dry at 20 MPa effective pressure.

Ultrasonic velocities were measured as a function of effective confining pressure. In general, the velocities are relatively fast and independent of pressure. The effect of saturation is also independent of pressure, and typically results in little change in compressional velocity and modest reduction in shear velocity. Some typical results are shown in Figure 1.

Observed pressure dependence of the compressional and shear velocities is weak in all samples tested. Averaged over the pressure range 10 to 30 MPa, compressional and shear velocities change by less than 0.25% per MPa change in effective confining pressure. This insensitivity to pressure is similar to that observed previously in studies of core from The Geysers (see Figure 2). Thus, despite the considerably higher porosities of the Awi 1-2 cores, the observed effects of pressure and saturation on the ultrasonic velocities are remarkably similar to that seen in The Geysers core.

Measured shear velocities correlate reasonably well with compressional velocities (Figure 3). Lahars and andesites span an overlapping range of velocities while the dacites (all from similar depths) are slow in comparison. The tuff sample has similar velocities to the dacites and the microdiorite falls within the fast end of the observed values for lahars and andesites. There appears to be little systematics with depth.

Andesites appear to exhibit a correlation between V_p and V_p/V_s ratio while in contrast, lahars are confined to a narrow range of V_p/V_s (see Figure 4). Correlation between velocities and porosity is weak, indicating that porosity is not the dominant controlling factor on the velocities.

The Effect of Saturation on Velocities

Physical insight into the effects of saturation on the measured velocities is gained by viewing the results in terms of computed dynamic moduli. Assuming that the samples are mechanically isotropic, the dynamic bulk (K) and shear (G) moduli are computed from the measured velocities and densities (ρ) as

$$G = \rho V_s^2$$

$$K = \rho V_p^2 - \frac{4}{3} G$$

Computed dynamic moduli for two representative samples are shown in Figure 5. The effect of brine saturation is to increase K and decrease G, with the effects being largely independent of pressure.

The increase in dynamic bulk modulus is thought to reflect poroelastic stiffening due primarily to the low frequency Biot mechanism. The decrease in the dynamic shear modulus is less well understood. Similar shear modulus reductions have been observed in core from The Geysers, indicating that a common physical model for these widely different reservoir rocks is appropriate. Among the six Awibengkok cores tested, shear modulus reductions range from 1.6 GPa to 3.8 GPa (see Table 2). These reductions are significant, amounting to 7% to 26% loss of shear modulus. Comparing these results with those from The Geysers, we find the the shear modulus reduction does not correlate well with porosity, but that the fractional shear modulus reduction does appear to correlate with the value of the dry shear modulus (Figure 7).

Table 2. Dynamic Shear Moduli and Shear Weakening for Selected Cores

Sample -	G_{dry} GPa	$G_{sat} - G_{dry}$ GPa	$(G_{sat} - G_{dry})/G_{dry}$ -
3100_1a	14.3	-3.8	-0.26
4072_7a	19.7	-3.0	-0.15
4125_3a	21.8	-1.8	-0.08
4504_4a	26.7	-2.8	-0.10
5091_1a	14.5	-2.2	-0.15
5513_6a	23.2	-1.6	-0.07

As a test to begin exploring the physical processes responsible for the shear weakening, one lahar sample has been tested while saturated with kerosene. Kerosene was selected because it has similar viscosity, density, and compressibility to brine, but is not chemically reactive in the same way. No shear weakening is observed upon saturation with kerosene (Figure 6). Note the shear modulus for the brine saturated case is significantly reduced (by 3 GPa) in comparison to the dry and kerosene saturated cases. This suggests that the shear weakening effect is the result of a rock/water chemical interaction of some type.

Discussion

In previous work on core samples from The Geysers geothermal field, it has been found that the dynamic shear modulus of the matrix weakens in the presence of water. Similar results are found for the Awi 1-2 cores. While the mechanism remains unclear, evidence suggests that the effect results from chemical rock/water interactions.

The observed losses in shear moduli with brine saturation have important implications for interpretation of field seismic data. Seismic identification of a developing steam cap may be hampered by the presence of such an effect. Upon drying, it is traditionally assumed that compressional velocities will decrease due to the dominance of poroelastic effects on the compressional velocity. Shear velocities will increase slightly due to the change in bulk density. Thus the signature of drying is thought to be lower Vp, lower Vp/Vs, and slightly elevated Vs. With shear weakening however, the loss of Vp upon drying is muted, and the rise in Vs is exaggerated. If shear weakening is strong enough (as it appears in these samples) the shear weakening effect can counteract the poroelastic effect, leading to little change in Vp upon drying. This dramatically changes the traditional interpretation of Vp anomalies in terms of saturation effects.

The narrow range of observed velocities combined with the general lack of effect of pressure on matrix velocities may suggest that controls on field scale seismic attributes will be dominated by properties of the fracture system.

References

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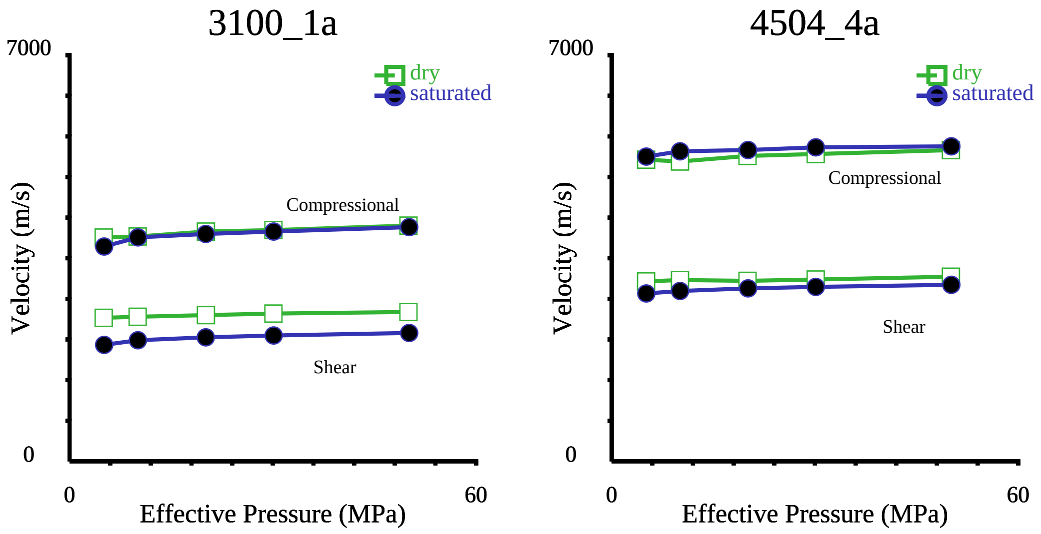

Figure 1: The effect pressure and brine saturation on two representative samples from Awi 1-2. There is little pressure effect on the velocities. Brine saturation leads to a modest reduction in shear velocities and little effect on the compressional velocities.

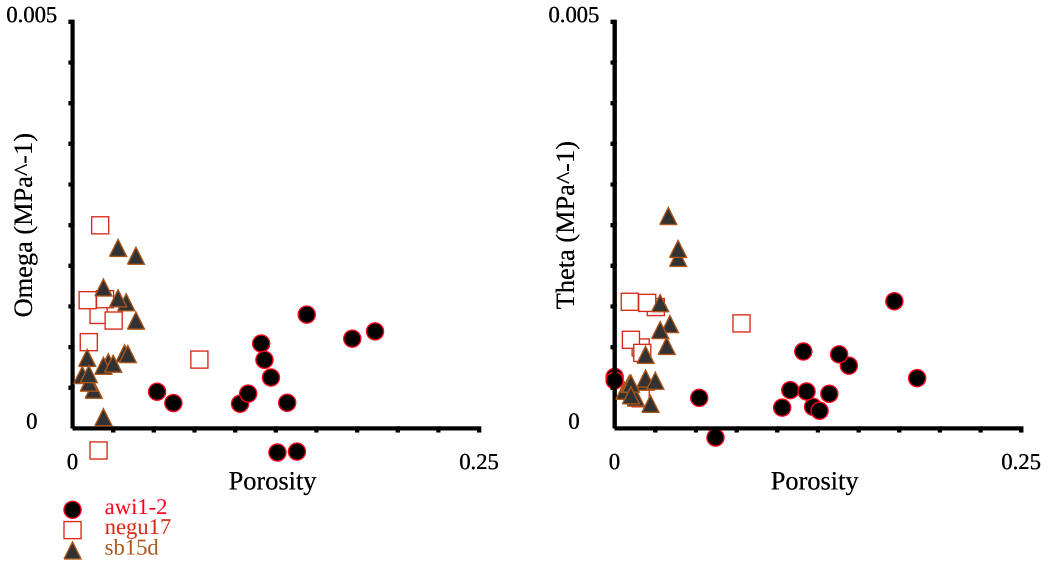

Figure 2: Observed pressure dependence of dry compressional and shear velocities, plotted as a function of porosity, for core samples from Awi 1-2 and Geysers coreholes NEGU17 and SB-15-D. In the plots, pressure dependence is defined as $\Omega = \Delta V_p/V_p\Delta P$ and $\Theta = \Delta V_s/V_s\Delta P$ over the pressure range from 10 MPa to 30 MPa. Note that despite systematic differences in porosity between the three sets of samples, the relative effects of pressure on the velocities is similar.

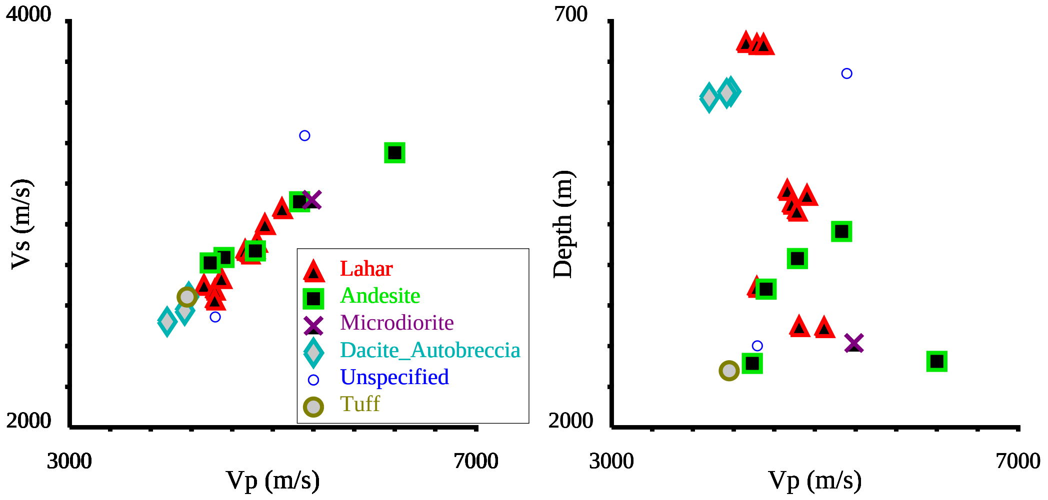

Figure 3: Summary of dry velocity data on Awi 1-2 samples. Vp correlates reasonably well with Vs, but there is no apparent trend in the velocities with depth. Lahars and andesites span similar variation in velocities.

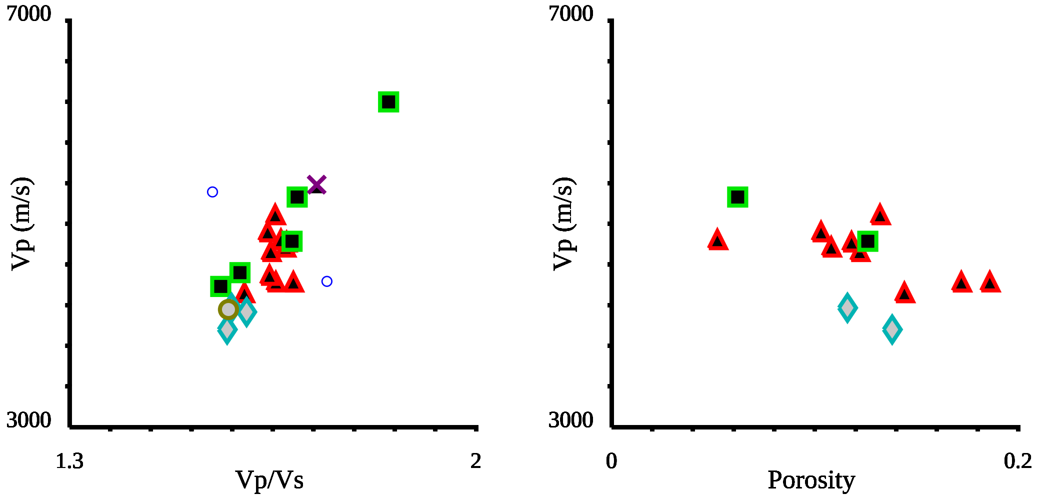

Figure 4: Andesites appear to exhibit a correlation between V_p and V_p/V_s, while lahars are confined to a narrow range of V_p/V_s. Porosity does not appear to be a strong controlling factor in determining the velocities.

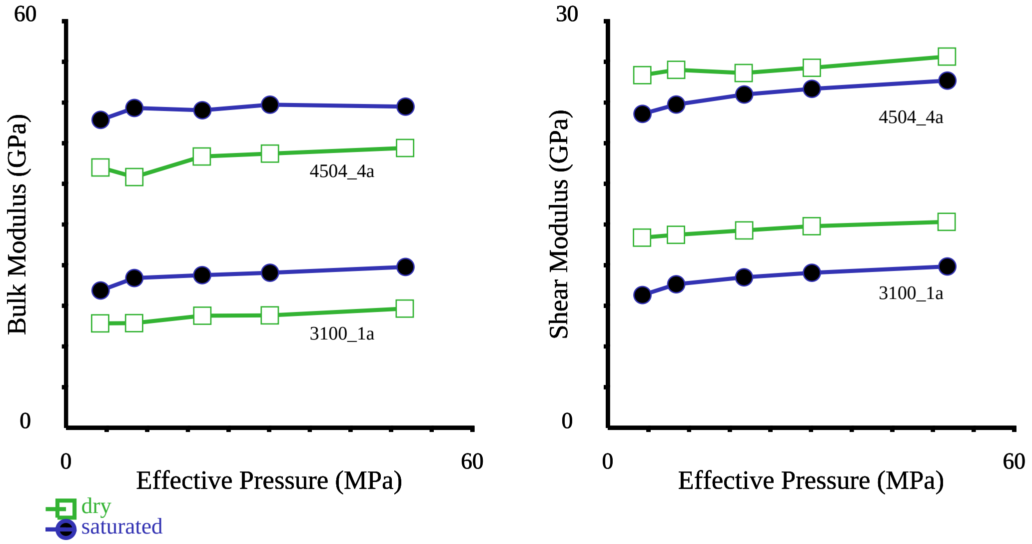

Figure 5: Dynamic elastic moduli as a function of saturation and pressure for two representative samples from Awi 1-2.

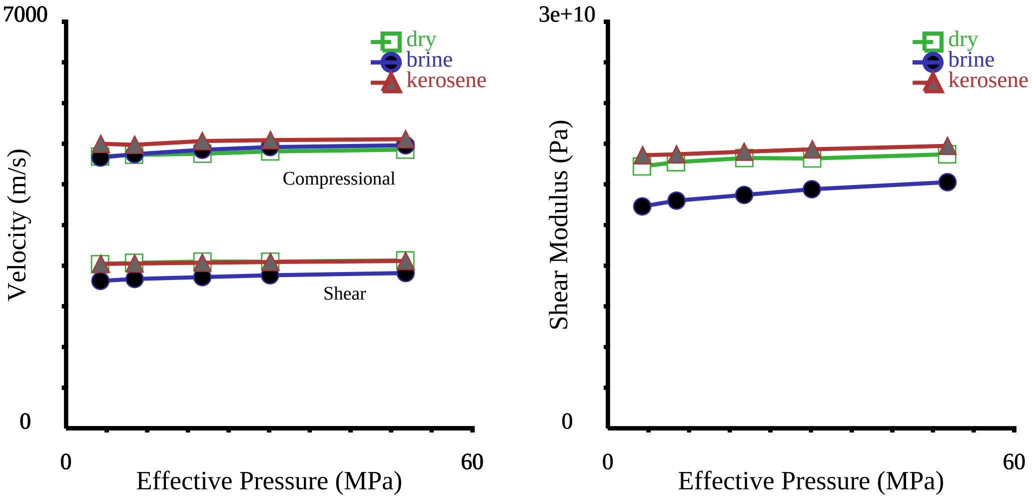

Figure 6: Comparison of dry, brine saturated, and kerosene saturated velocities and dynamic shear moduli for a lahar sample from Awi 1-2.

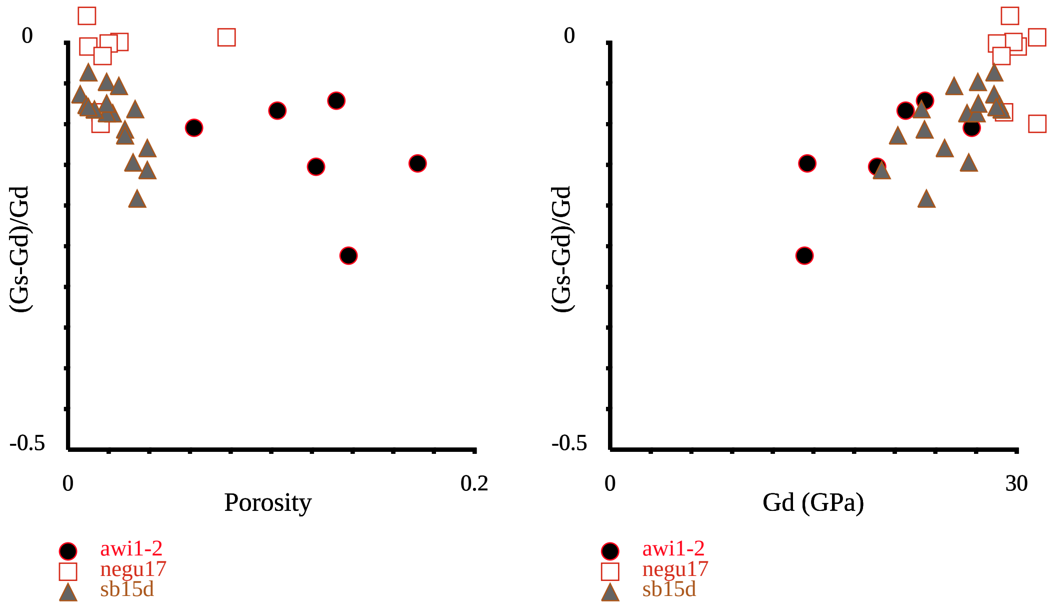

Figure 7: Factional loss in shear modulus upon brine saturation as a function of sample porosity and dry shear modulus. A possible correlation between the fractional loss and the dry shear modulus suggests a link between the weakening and variables controlling the shear modulus itself.