The Effects of Pressure, Temperature, and Lithology on Seismic Wave Velocities for Rocks from the Larderello Geothermal Field

Bruno Tarquini*, Mauro Cameli*, Claudio Donati*, and Randolph J. Martin, III†

*Enel/DPT/VDAG, via A. Pisano, 120 Pisa, Italy;
†New England Research, Inc., White River Jct., VT

Key Words: seismic velocity, seismic attenuation, rock properties, laboratory study

1. ABSTRACT

A suite of laboratory measurements were performed on oriented low porosity metamorphic rock cores recovered from several geothermal wells near Larderello. Compressional and shear wave velocities were measured as a function of orientation with respect to the foliation, effective confining pressure, and temperature. Seismic wave attenuation was computed for several data sets. Permeability was measured on the rocks from one well. All the rocks were slightly anisotropic, less than 15%in general. Seismic wave velocities exhibited a small pressure dependence. Even at the water-steam transition the change in velocity was less than 1.5%. All the data suggests that the rocks contain few microcracks and the anisotropy is, for the most part, due to mineral orientation.

2. INTRODUCTION

A project was initialed to develop a method of predicting the seismic signature of deep (> 2000 m) permeable or fractured zones within the metamorphic basement at the Italian geothermal fields of Larderello and Monte Amiata. The study was motivated by the need to identify and delineate deep geothermal reservoirs from characteristic signatures on surface seismic sections and Vertical Seismic Profiles (VSP), in combination with other geophysical and geological data. Another important objective is to determine the structure beneath the geothermal fields in the depth range of 1-10 km. Important elements of this structure are the location and shape of the batholith that is the heat source for the geothermal fields, and the position of the deep seated faults along which the reservoir fluid circulates. These features of the structure are the specific target.

Production from these reservoirs is strongly correlated with normal faults (Batini et al., 1985a), indicating that the reservoir fluids circulate along these faults, which must be deep seated to reach the batholith that is inferred to supply the heat for the field. After a long history of exploitation of these shallow geothermal fields in anhydrites and dolomites of the Tuscan Nappe, declining production has led to the drilling of several deep wells into the deeper parts of the section containing metamorphic rocks. The deep drilling found fractured and/or permeable layers in the metamorphic rocks, some of which constituted geothermal reservoirs at depths of 2500 -3500 m.

The identification of drilling targets by geological or geophysical means starts with a structural interpretation. One important structural question is the location and shape of the batholith that is believed to be the heat source of the geothermal field (Batini et al., 1985b). So far it remains undetected. A more specific structural question is the deep configuration of normal faults that seem to play an important role in fluid circulation. The occurrence of earthquakes at depths of up to 8 km (Batini et al., 1985c) indicates that the batholith must lie at least that deep, and that the faulting extends to this depth. This is substantially deeper than the scope of geophysical investigations to date.

There are a number of approaches that have been tried to solve these problems. The most detailed is a seismic characterization of fractured and/or permeable zones using cores, well logs, VSP and surface seismic data to allow prediction of the seismic signature from productive zones and derivation of the rock properties needed to guide deviated drilling from seismic data.

A series of experiments were carried out on samples recovered from seven geothermal wells near Larderello, Italy. The study was designed to assess the anisotropy of the samples, the influence of temperature and pressure on velocity and anisotropy, the effect of pressure on permeability, and the magnitude of seismic wave attenuation for representative samples. The primary goal was to support theoretical seismic models used to delineate major fractures which are potential regions of steam production. In order to develop an accurate model, it is necessary to know how the seismic wave velocity varies with orientation, depth, and temperature. Furthermore, it is necessary to have a realistic value for seismic wave attenuation so that the amplitude of the propagating waves can be definitively assessed. Finally, it seemed prudent to measure the permeability of at least one representative sample as a function of orientation. If the rocks were truly anisotropic then it was anticipated that both the seismic wave velocities, as well as the permeability, would vary with the preferred structure of the rock.

3. EXPERIMENT PROCEDURE

Measurements were conducted on rocks recovered from seven wells as enumerated in Table I. A representative core from each well was studied as a function of orientation. From each core, three (3) oriented specimens were prepared. Assuming that the initial core was vertical, one specimen was prepared parallel to the core axis, a second at 45^{o} to the core axis, and a thud at 90^{o} to the core axis $\phi < 1\%$. Ideally, if the material was transversely anisotropic, and the foliation or bedding was perpendicular to the borehole axis, that is horizontal, the compressional wave velocity should be lowest for vertical propagation directions and greatest for waves propagating within the bedding plane (Lo et al., 1986). Similarly, the permeability should be greatest for flow directions parallel to the bedding plane and lowest for vertical flow directions.

Room temperature velocity measurements were carried out as a function of confining pressure on oriented specimens from each of the seven wells. All the samples were run saturated with a small positive pore pressure to ensure complete saturation. The permeability measurements were also canied out on Monteverdi #5, 2073.4. The elevated temperature measurements were carried out on Monteverdi #7, 3483.7 and Sasso #22, 2894.5. The attenuation was calculated for the velocity results obtained on Monteverdi #7.

3.1. Velocity Anisotropy

Compressional and two polarized shear wave velocities were measured on each test specimen as a function of confining pressure for a fixed pore pressure of 5 MPa. For all samples tested the compressional wave velocity was lowest in the vertical direction and greatest in the horizontal direction. Similarly, the polarized shear wave velocities were lowest for vibration directions in the vertical direction and greatest when the vibration direction was parallel to the foliation. Furthermore, the shear wave velocities were independent of orientation in the plane of foliation. These results are consistent with a transversely anisotropic characterization of the rocks (Lo et al., 1986). The data are summarized in Table I. A brief description of the lithology is presented for each suite of test specimens. The compressional and

TABLE I

Compressional and shear wave velocities at an effective pressure of 50 MPa as a function of orientation with respect to foliations for specimens recovered from geothermal wells near Larderello.

Well; Depth, m	Lithology	V_p Vertical km s^{-1}	V_p Horizontal km s^{-1}	V_s Vertical km s^{-1}	V_s Horizontal km s^{-1}
Monteverdi #2 **886.6**	Cataclasite made up of quartz, albite, and pyrite crystals cemented by secondary calcite	**5.757**	**6.116**	**3.125**	**3.428**
Monteverdi #5 **2073.4**	Quartz-muscovitic schist, Mycaschist formation	**5.327**	**6.104**	**2.946**	**3.599**
Monteverdi #7 **3483.7**	Granite with cordierite	**5.619**	**5.639**	**3.034**	**3.085**
Bagnore #22 **1301.3**	Carbonatic-anydritic breccia, Burano formation	**5.904**	**6.090**	**3.085**	**3.309**
Sasso #22 **2894.5**	Quartz-mylonite with subvertical fractures, Mylonitic Gneiss formation, Secondary fractures (sub-vertical) filled with quartz and chlorite	**5.559**	**5.932**	**3.140**	**3.384**
Sughere #1 **2795.4**	Quartz-feldspatic Mylonite, Mylonitic Gneiss Formation, Subvertical fractures filled with quartz, epidote, titanite, and chlorite	**5.514**	**6.047**	**3.057**	**3.435**
San Pompeo #2 **2718.1**	Quartz-chloritic schist, Mycaschists formation	**5.117**	**5.866**	**2.922**	**3.476**

shear wave velocities at confining pressure of **55** MPa and a pore water pressure of 5 MPa are given for propagation directions parallel (vertical) and normal (horizontal) to the borehole axis. In most cases, the foliation is horizontal.

Perhaps the most interesting aspect of the velocity measurements is the small influence of confining pressure on seismic wave velocities. For a highly cracked or layered material, a large increase in velocity would be anticipated at pressures between 0 and **25** MPa. The only samples to exhibit such a pressure dependence were the most anisotropic samples from the Monteverdi #5 and the San Pompeo **#2** wells. The remaining samples not only exhibited a small anisotropy, but also a very small pressure dependence. The velocity data obtained on cores of Monteverdi **#5, 2073.4** oriented parallel and normal to the foliation are presented in Figure 1. Based on these observations, it is clear that the samples contained very few microcracks and fissures that would contribute to a strong pressure dependence for velocity. This is a very important and quite surprising result for metamorphic rocks.

3.2. High Temperature and Pressure Velocity Measurements

Compressional and shear wave velocities were measured as a function of temperature, confining pressure, and pore pressure on three specimens from Monteverdi **#7** and **Sasso #22.** Temperatures were increased to 120°C and measurements were conducted at effective confining pressure to **70** MPa for pore pressures between **0.2** and **10** MPa. It was expected that as the pore pressure decreased below 1 MPa or so at temperatures above 100°C that the water would undergo a phase transition to steam and the velocity would decrease perceptibly. A small change in velocity was observed as the pore pressure passed through the water-steam transition. In fact, for Monteverdi #7, the change in compressional wave velocity at an effective confining pressure of **30** MPa was less than **1.5%.** Similar changes were observed for the compressional waves on Sasso #22 and on the shear wave velocities of all specimens.

The most impressive result of the high temperature velocity measurements is the absence of a pronounced reduction in either the compressional and shear wave velocities in the vicinity of the water-steam phase transition at temperatures above 100°C. The implications of this observation are significant for the interpretation of seismic data. These results suggest that any major decreases in velocity will be associated with phase changes in fractures and fracture zones at depth, and are not the result of phase changes within the rock matrix.

3.3. Seismic Wave Attenuation

The seismic wave attenuation was calculated as a function of pressure for the vertical specimen form Monteverdi **#7, 3483.7.** The attenuation was calculated as a function of Confining pressure using a spectral ratio technique. The Qs were high at the lowest pressure and rapidly increased with confining pressure until the upper limit of resolution was reached, a Q of approximately **400.** Both P and S wave quality factors were above 400 at confining pressures appropriate for the depth from which the sample was taken. Therefore, seismic wave attenuation for the intact rock is very low, and high frequencies propagate very efficiently. The high Qs logically correlate with the lack of substantial pressure dependence in the velocity data, and indicate an absence of a substantial microcrack population.

3.4. Permeability

Permeability was measured on three specimens from Monteverdi #5, **2073.4.** Permeability was measured using the pulse-decay technique at effective confining pressures of **25,** 50 and **100** MPa. The pore pressure was constant at **10** MPa. The permeability was directly related to the orientation of the sample. For example, at an effective pressure of **25** MPa the permeability was greatest for the specimen with a flow direction parallel to the foliation; the permeability was **3,340** nanoDarcy. The **45°** specimen exhibited a permeability of **3.8** nanoDarcy at an effective pressure of **25** MPa, while the specimen with the flow direction normal to the foliation displayed a permeability less than **0.1** nanoDarcy. With increasing pressure the permeability decreased; increasing the effective pressure form **25** to **100** MPa resulted in a twenty fold decrease in the permeability for the 0° and 45° specimens. The strong anisotropy effect observed in permeability was also present in the velocity measurements. The compressional wave anisotropy from Monteverdi **#5** specimens was **12.7%.**

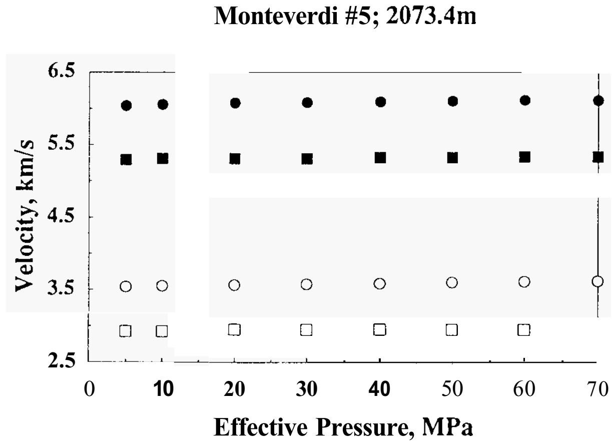

Figure 1: Compressional and shear wave velocities measured on specimens of a strongly anisotropic quartz-muscovite schist are plotted as a function of effective confining pressure. Circles indicate propagation in the plane of the foliation; squares indicate propagation normal to the foliation. Solid symbols are P waves; open symbols are S waves.

The fact that the permeability was greatest parallel to the foliation planes of the schist is consistent with the transverse anisotropic behavior exhibited by the acoustic data. While the permeability decreased with increasing confining pressure, the magnitude of the anisotropy remained relatively constant. It is difficult to say much more about the permeability since the observed values were below the resolution of the system for specimens with flow directions normal to the foliation plane.

4. CONCLUSIONS

The results of the velocity, attenuation, and permeability measurements form a self-consistent data set which reveal a great deal about the microstructure of the rocks in the geothermal fields in the vicinity of Larderello. The change in velocity with increasing confining pressure is nearly linear for most of the samples that were studied. Several samples that displayed a large pressure sensitivity at low pressures also exhibited the greatest velocity anisotropy. These rocks were recovered from Monteverdi #5 and San Pompeo #2. The velocity anisotropy was less than 10% for all the wells except Monteverdi #5 and San Pompeo #2. The magnitude of the anisotropy showed a slight decrease with increasing confining pressure. However, confining pressures of 70 MPa were not sufficient to completely erraticate the inherent anisotropy in the material.

The most important result inferred from the data is that the metamorphic rocks in the geothermal field at Larderello contain an extremely small density of microcracks. Since microcracks control the change in velocity at low pressures, the absence of microcracks is reflected by the absence of a strong pressure dependence on compressional and shear wave velocities, the low seismic wave attenuation, and the absence of a perceptible change in velocity as the pore fluid passes through the water-steam transition at temperatures greater than 100°C. The permeability measurements also reflect a low microcrack density. The fact that the permeabilities range from subnanoDarcy to several hundred nanoDarcy at characteristic recovery depths also suggest that there are very few interconnected cracks within the rocks.

In light of the experimental data, it appears that major structural features and predominantly fractures will be the main source of velocity and permeability variations within the geothermal field. For the most part, the rocks have a low seismic wave anisotropy and a small change in velocity with pressure. Consequently, in the absence of any lithological changes, fractures will be the predominant structural feature to be interpreted with seismic data.

5. REFERENCES

Batini, F., P. Castellucci and G. Neri (1985a). The Travale geothermal field. ***Geothermics*** *14.255-272.*

Batini, F. , G. Bertini, G. Gianelli, E. Pandeli, M. Puxeddu and I.M. Villa (1985b). Deep structure, age and evolution of the Larderello-Travale geothermal field. ***Geothermal Resources Council Trans. 9,*** Part 1.

Lo, T., K. B. Coyner, and M.N. Toksoz, (1986). Experimental Determination of Elastic Anisotropy of Berea Sandstone, Chicopee Shale, and Chelmsford Granite. ***Geophysics,51,*** 164-171.