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CONTRIBUTION OF THE SEISMIC REFLECTION METHOD TO THE LOCATION OF DEEP FRACTURED LEVELS IN THE GEOTHERMAL FIELDS OF SOUTHERN TUSCANY (CENTRAL ITALY)

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ABSTRACT

For more than twenty years ENEL has been employing the seismic reflection method for geothermal exploration in Central Italy. Initially, this methodology was used for geological-structural goals, but subsequently it has been more and more adopted to locate productive zones in the deep reservoirs. The large amount of data (about 600 km of 2D seismic traverses, about 20 km^2 of 3D seismics and more than 30 VSPs), unique in geothermal research, has enabled us to increase our understanding of seismic signals in the particular geologic environment of the deep Tuscan geothermal reservoirs mostly made up of metamorphic and intrusive rocks. The hypothesis that some seismic reflections could correspond to fractured rocks was investigated with two different methodological approaches: one strictly theoretical, the other empirical-statistical.

The former tries to reconstruct the synthetic seismograms of fractured rocks in a steam reservoir and compares them to the experimental signals. The latter investigates the statistical relationships between reservoir data (injectivity, productivity) and reflection signals. This statistic study was carried out on 83 deep geothermal wells. Both these approaches suggest that some velocity anomalies (i.e. seismic reflections) be linked to fractured and thus potentially productive layers.

1. INTRODUCTION

The first tests of seismic reflection prospecting were conducted in 1974 in the Larderello geothermal field. The initial aim of seismic prospecting was to reconstruct the structural feature of the geologic formations involved in geothermal phenomenon even in the marginal and less known zones of the field.

One of the goals was to gather new data that could allow a better knowledge of the boundaries of the geothermal area. As research went on, going deeper in the metamorphic formations underlying the shallow carbonate reservoir, it was clear that the relationship between geological structures and the occurrence of geothermal resources was no longer valid. It was then necessary to find new correlation elements even if they were empirical.

As new seismic data were acquired, it became clear that the seismic method could provide more than the definition of geological structure, namely, information directly related to geothermal production.

Reflection seismics, moreover, turned out to be the only methodology able to provide resolution useful for operative targets deeper than 3 km. Even inside the formations of the metamorphic basement, it is possible to observe reflectors that are often very sharp and continuous, sometimes weaker and non-continuous, but always validated at the crossing of different or adjacent seismic lines.

The presence of reflections within formations characterised by quite homogeneous lithology allows to formulate the hypothesis that such signals could be caused by layers whose physical parameters can vary due to fracturing and by the eventual fluids occurrence. Such reflections sometimes show signal anomalies quite similar to bright spots, which in oil research are generally associated to gaseous fluids.

2. STUDY AREA

The Larderello-Travale geothermal field was chosen to verify the contribution of the seismic reflection method in deep geothermal exploration. Here ENEL carried out about 600 Km of seismic lines, 20 Km^2 of 3D seismics (Fig.1) and more than 30 VSPs (Vertical Seismic Profiles).

The area is located in correspondence to a structural high of the Tuscan Nappe (radiolarites, marls, limestones, anhydrites) and the Tectonic Wedges Complex (anhydrites, phyllites and quartzites) which constitute the shallow reservoir (Pandeli *et al.,* 1991). This reservoir is characterised by high secondary permeability at its top.

These formations irregularly overlie a metamorphic substratum made up of phyllites, micaschists, gneiss and granites. The deep wells revealed the presence of fractured layers inside this substratum with an increase of temperature and pressure with depth. The Flysch and Neogene sediments cover the reservoir formations and act as a cap rock for the geothermal system. The fluids, tapped within 4000 m depth, show vaporstatic pressures (generally <8 MPa) and temperatures between 200° and 350°C (Barelli *et al*., 1995).

3. SEISMIC DATA AND RELEVANT PROBLEMS

The greatest reflectivity coefficients regard the upper formational contacts as Neogenic sediments/Flysch and Flysch/Evaporites (Burano Anhydrites). At the same time a remarkable (of one order of magnitude) decrease of the reflectivity coefficients occurs at the lower contacts, such as Evaporites/Tectonic Wedges, Phyllites/Micaschists and Micaschists/Gneiss.

This implies that on the seismic lines the geological contacts from the surface down to the base of the evaporitic formations are quite well defined, while, generally, those inside the underlying metamorphic basement, are poorly outlined.

However, in the metamorphic basement, strong and extended seismic signals are recorded; the main one is the so-called K horizon whose nature is not well ascertained yet, but it is probably linked to geothermal fluid occurrence. (Cameli *et al*., 1993).

Between the top of the metamorphic basement and the K horizon, further seismic reflections have been observed, sometimes characterised by high energy (e.g. Fig.2, Fig.3). We have recently focused our attention on this zone, where deep reservoirs have been discovered.

Considering that in this interval there are no single formational changes able to produce important seismic reflections, we are investigating the existence of a correlation between the presence of important seismic reflections and the peculiar physical conditions of well-defined rock intervals. In this zone the occurrence of high reflectivity coefficients is shown by considerable variations in the main elastic parameters, recorded by the borehole logs in correspondence of the fractured fluid bearing layers. Until now seismic modelling, carried out on the most representative cases, has always confirmed the validity of the work hypothesis that predicts energetic seismic reflections within the deep geothermal reservoirs. Such reflections must be caused by fractured intervals showing a minimum thickness of a few meters, sub-horizontal geometry and lateral extent of at least some tens of meters (Batini *et al*, 1990).

4. DISCUSSION

The above working hypothesis has been carried out following both a theoretical and empirical approach. The former studies the cause and effect relationships between interesting petrophysical situations and the seismic response. The latter verifies the nature of the reflections where these have been directly penetrated by the well.

4.1 Theoretical Study

Seismic techniques, borrowed from hydrocarbon research, have been applied to Italian geothermal exploration since the early 1980's (Batini and Nicolich, 1985, Batini *et al.* 1990, Cameli *et al.* 1995). At that time evidence of seismic reservoir characterisation was obtained.

The aim of this theoretical study is to verify the feasibility of an innovative seismic approach to the detection of geothermal reservoirs. We refer to the application to the geothermal exploration of techniques that are well known in the hydrocarbon exploration, such as wavelet processing and calibrated acoustic impedance sections; and Amplitude Versus Offset (AVO) analysis (Mazzotti, 1990, Mazzotti *et al*., 1994). The goal is to determine whether the peculiar petrophysical conditions, in terms of temperature, pressure, injectivity and steam production, are able to produce distinctive anomalies either on post-stack or on pre-stack seismic data. To this end, from the borehole we acquired data information on 8 different wells in the Larderello-Travale area, the seismic velocities and densities and the relevant petrophysical parameters at the fractured and steam saturated levels. The final task was to compute the expected seismic response.

Fig. 4 refers to a productive well and shows the blocked logs of density and P-wave velocity, and the corresponding normal-incidence reflection coefficients and synthetic seismogram in a time window which includes the production zone only. It is interesting to observe that there is a large reduction of both the velocity and density at the fractured production level (3710 m of depth) and high amplitude of the reflection coefficients and of the synthetic reflection waveforms. These were computed by convolution with three different zero phase Ricker wavelets at the peak frequencies as shown in the figure.

Since no information on shear wave velocity was available, the AVO response (Fig. 5) was computed following a "what if" procedure, that is, we varied the values of the shear velocities to reproduce possible Vp/Vs ratios of the producing level and of embedding rocks. Based on the results of lab measurements and of theoretical rock physics, the presence of a gaseous phase (steam) in the fractures should cause a decrease in the Vp/Vs ratio. In this case, the modulus of the reflection coefficient, on the interface separating the overlying layer from the fractured reservoir, increases or remains nearly constant with the angle of incidence. Thus, increasing or constant AVO trends may be peculiar to fractured, steam saturated layers and may be detected on real seismic data. In contrast, non-productive levels should give rise to decreasing reflection coefficients and similarly decreasing AVOs.

4.2 Empirical Study

An empirical analysis has been carried out on the seismic reflections occurring inside the metamorphic basement where fractures and production well data are available (e.g. Fig. 6). The results are summarised in table 1.

The fracture data utilised refer to the drilled geothermal wells and are subdivided into three groups: industrially producing fractures (PF); scarcely producing fractures (SPF); not producing fractures, notwithstanding the total loss of circulation during drilling and/or important absorption levels evidenced by specific reservoir tests (TLC).

The correlation quality between the working hypothesis, that is fractured levels producing distinctive seismic reflections, and the real data were evaluated according to the deviation percentage between the reflection depth and the closest fracture depth measured in the well. Four deviation classes have been considered: < 3%, 3-5%, 5-10%, > 10% (as an example at 2000 m depth, 10% deviation corresponds to a difference of 200 m between the depth of the reflection and the depth of the closest fracture).

To complete the case histories, the following events have also been considered:

- -neither seismic reflections nor fractures (NN);
- -no fracture detected in correspondence of a well defined seismic reflection (NF);
- -no visible reflection in correspondence of a detected fracture (NR).

On the whole, it has been possible to analyse 83 wells where either seismic information or fracturing information is available. The seismic data set is represented by 286 seismic reflections (117 from VSP and 169 from surface seismic lines). The column "n. events" (table 1) lists the numbers of reflections correlating with fractures according to the deviation value, for the different types of fracturing, and the kind of seismic survey considered. The percentages, listed in the adjacent column, refer to the total number of events.

From the first row of the table: 24 reflections recorded by VSP, corresponding to 20.5 % of the total, correlate with producing fractures, being the depth deviation < 3% (less than 90 m at 3000 m depth). Similarly for the surface seismic, the same type of correlation has been found on 23 of the examined cases, that is on 13.6 % of the total. Extending the analysis to 10% deviation, this correlation rises to 29% for VSP reflections and to 29.6% for those ones from the seismic line.

Since an average of 2.6 reflections from VSP surveys and 1.6 from seismic lines have been recorded, it follows that almost one reflection for each well in the first case, and one for two wells in the second one, may correspond to productive fractures.

Finally, if we consider most seismic reflections (VSP + seismic lines) and most fractures (PF + SPF + TLC) irrespective of the number of reflections for a single well we obtain:

40.9% of the events correlates with deviation	< 3%
18.5% of the events correlates with deviation	3 - 5%
13.6% of the events correlates with deviation	5 - 10%
26.9% of the events do not correlate with deviation	> 10%

the same analysis, carried out separately for the two kinds of survey (Fig.7), provides the VSP data:

51.3% of the events correlates with deviation	< 3%
17.9% of the events correlates with deviation	3 - 5%
7.7% of the events correlates with deviation	5 - 10%
23.1%does not correlate with deviation	> 10%)

and for the seismic lines data:

33.7% of the events correlates with deviation	< 3%
18.9% of the events correlates with deviation	3 - 5%
17.8% of the events correlates with deviation	5 - 10%
29.6% does not correlate with deviation	> 10%

To summarise, 73% of seismic reflections correspond to fractured zones, being the depth deviation less than 10%, while the rest (27%) does not correlate or the correlation shows a deviation > 10%.

Similarly, considering separately VSP reflections and surface seismics, we obtain 76.9% and 70.4% respectively that do correlate, while 23.1% and 29.6% do not correlate.

The maximum correspondence occurs systematically in the minimum deviation class and tends to diminish as the deviation class increases.

This is particularly evident from the VSP data. Since the correlation percentage with the more ascertained and tested fractures (PF and SPF) reaches the maximum values (20.5 and 17.1% respectively) in the minimum deviation class, while it dramatically decreases (5.1 and 4.3% respectively) in the next one. The VSP data are much more sensitive compared to seismic surface line data. This is due to the fact that the data quality of VSPs allows a better estimation of the depth of the relevant signals.

In contrast, this behaviour is less evidenced by the TLC fractures. This is probably due to the fact that in this case the depth of the fracture is itself more uncertain.

The high resolution power of VSP determines also a quite high percentage (17,1%) of reflections that do not correlate with any fracture (NF) and consequently no NN or NR case. These signals have to be ascribed to other causes, such as small-scale lithological variations, mineralisations and so on.

5. CONCLUSIONS

Both the theoretical feasibility study and the experimental investigation indicate that fractured, steam saturated levels give rise to distinctive and potentially diagnostic seismic features. These may occur both in a pre-stack phase, manifest as AVO anomalies, and in a post-stack phase, as high amplitude signals. The detection of such features requires appropriate seismic field acquisition and accurate seismic processing, including wavelet processing and true amplitude and phase control.

The results of the empirical study show that, within the Larderello-Travale deep reservoir, 73% of the seismic reflections are related to permeability with a depth deviation of less than 10%. Furthermore, 29% of the above generic permeability corresponds to industrially productive fractures.

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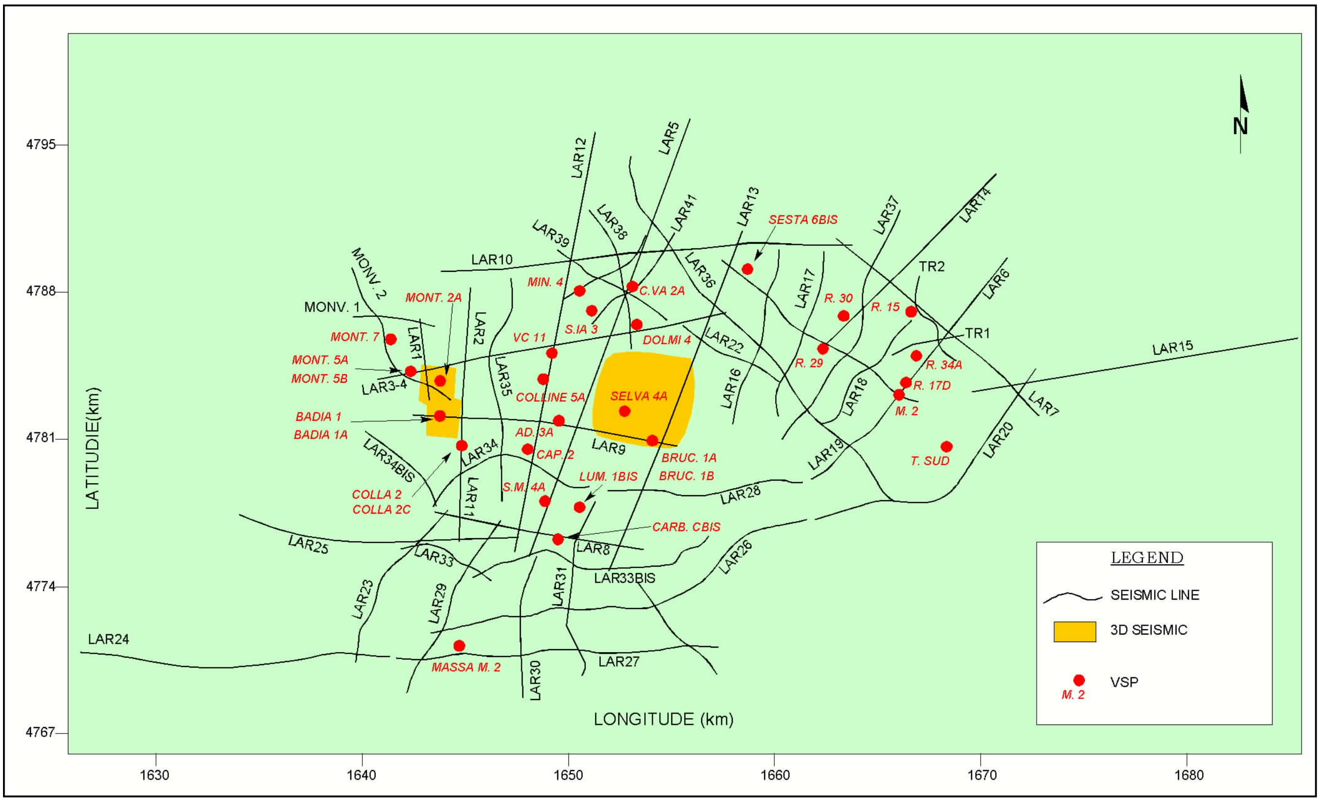


Fig.1 - Location map of seismic surveys (Larderello - Travale).

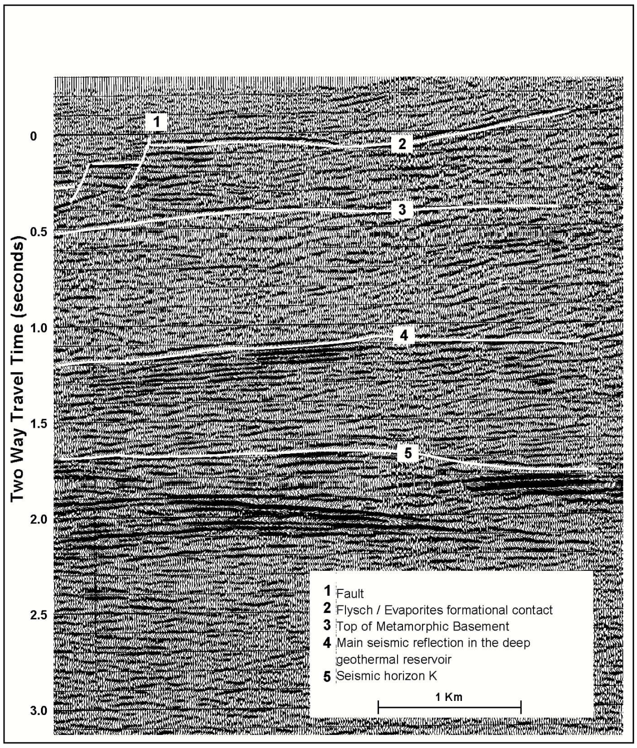


FIG.2 - Part of the seismic line LAR36 (stacked data).

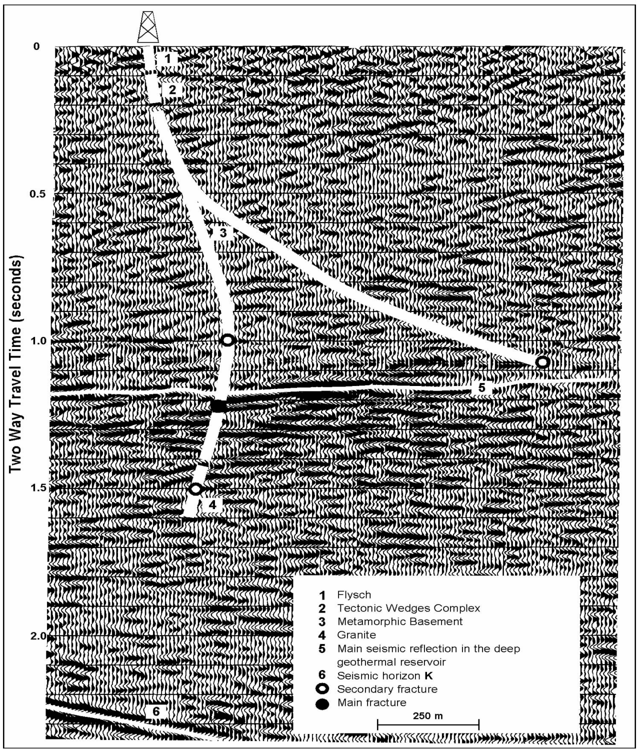


Fig.3 - Part of the seismic line LAR21 (migrated data) and projection of two directional wells.

Tab.1 - Fracture-reflection correlation quality.

CORRELATION QUALITY Fracture/Reflec depth deviation	REFLECTIONS SET VSP n. events	VSP %	Seismic lines n. events	Seismic lines %
PF				
< 3%	24	20.5	23	13.6
3÷5%	6	5.1	10	5.9
5÷10%	4	3.4	17	10.1
> 10%	1	1.0	3	1.8
Subtotal	*35*	*30*	*53*	*31.4*
SPF				
< 3%	20	17.1	15	8.9
3÷5%	5	4.3	8	4.7
5÷10%	1	0.8	4	2.4
> 10%	0	0	1	0.6
Subtotal	*26*	*22.2*	*28*	*16.6*
TLC				
< 3%	16	13.7	14	8.3
3÷5%	10	8.5	14	8.3
5÷10%	4	3.4	9	5.3
> 10%	6	5.1	9	5.3
Subtotal	*36*	*30.7*	*46*	*27.2*
NN				
Subtotal	*0*	*0*	*5*	*2.9*
NF				
Subtotal	*20*	*17.1*	*24*	*14.2*
NR				
Subtotal	*0*	*0*	*13*	*7.7*
TOTAL	*117*	*100*	*169*	*100*

PF Productive Fracture
SPF Scarcely Productive Fracture
TLC Total Loss of Circulation
NN No fracture - No reflection
NF No Fracture
NR No Reflection

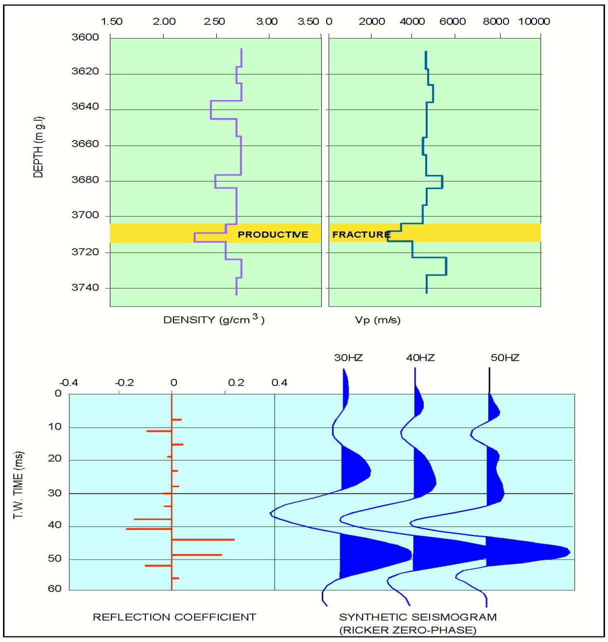


Fig.4 - Synthetic seismogram of a productive fracture in a deep well of Larderello - Travale area.

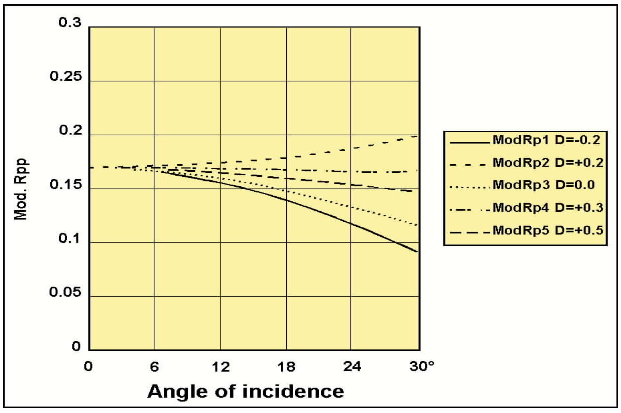
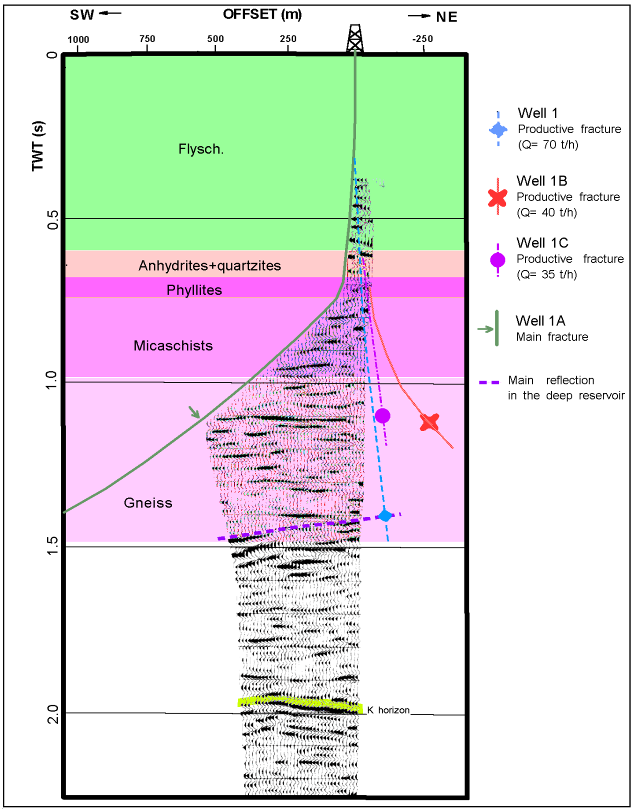


Fig.5 - Reflection coefficient modulus versus angle of incidence referred to the target of 3710 m.



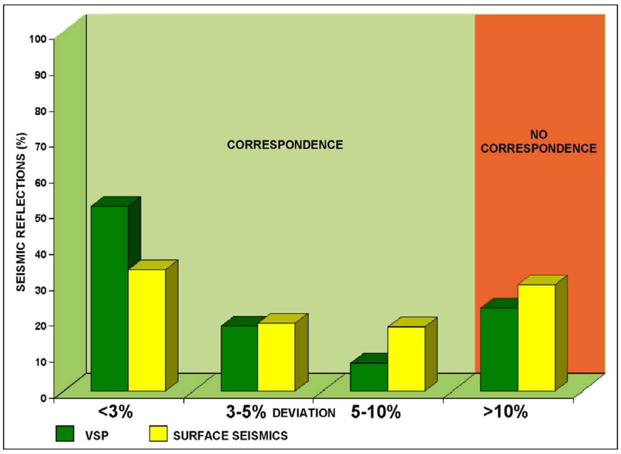


Fig.7 - Empirical correspondence between seismic reflections and fractures.

Fig.6 - VSP of directional wells exploring metamorphic basement.