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GEOPHYSICAL WELL LOGGING- A CONTRIBUTION TO THE FRACTURES CHARACTERIZATION.

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ABSTRACT

The need of a proper reconstruction of faults and fracture systems crossed during the well drilling is one of the most important feature for the deep exploration of a geothermal reservoir.

The geophysical well logging have been always utilized for geological and stratigraphic determinations, for the measurement of the main physical characteristics in order to provide calibration parameters for the surface geophysical surveys and for a qualitative localization of fractured and potential productive layers. Recent and specialized techniques and sensors for the detection of geometrical-structural parameters are now widely used.

One of them, the Circumferential Borehole Imaging Log (CBIL), when utilized for potential fractured layers already tagged by other techniques (as acoustic Wave Forms), has been proved as very effective and detailed.

We applied a complete set of this techniques in a deep well of the Larderello-Travale geothermal field, and a detailed analysis and characterization of the fractures was performed. The standard well-testing procedure was also applied, in order to match the results from the different approaches. A satisfactory correspondence was achieved. A preliminary comparison between the geometrical parameters of the fractures and their productivity was also carried out.

INTRODUCTION

In the last 30-35 years the geothermal exploration in Italy has gradually changed its targets.

Up to the mid 70's, the average depth of the geothermal wells was of about 1000 m, with the aim to reach a first and shallow reservoir hosted in a carbonate-anhydrite formation. This reservoir is characterized by a very high permeability due to a wide and diffuse system of fractures.

Subsequently, in order to increase the energy production from geothermal resources, a program of deep exploration started in the Larderello and Travale areas, the oldest Italian geothermal fields.

The average depth of the deep wells generally varies between 3000 and 3500 m, but in some cases a depth of over 4000 m has been reached. The exploration target of these wells is a deep reservoir hosted in a metamorphic basement and/or granitic bodies, where geothermal fluids with a temperature of 300°C and a pressure of 7 MPa can be found (Barelli et al., 2000).

The deep exploration enlarged the edges of the exploitable geothermal field and evidenced that at a depth of 3000 m b.s.l. the geothermal fields of Larderello and Travale belong to the same deep reservoir, with the same temperature and pressure environment (Fig. 1).

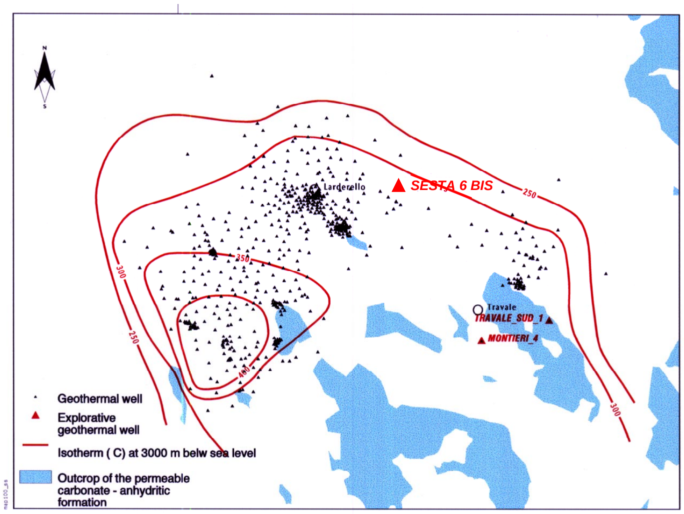

Fig. 1 - Larderello-Travale geothermal field: temperature contour lines at a depth of 3000 m b.s.l.

Differently from the shallow reservoir, in the deep one the fractured systems are not homogeneously distributed, but are confined in very localized levels of depth and are not correlated with specific geological features.

As a consequence of the high cost of the deep drilling, many efforts are in progress in order to find a technical - scientific approach able to reduce the mining risk by means of the reconstruction of a predictive geo - structural model.

Advanced analysis of seismic reflection data (Cameli et al. 2000) and innovative techniques of well seismic measurements (Batini et al. 1990, 2001) are giving a valid contribution to the detection of deep fractured levels.

The characterization of the fractures in terms of typology and geometric parameters to be correlated to their productive characteristics is extremely important for a complete and detailed delineation of the structural model. In this framework a relevant role is certainly played by updated geophysical well logging techniques.

THE GOAL AND THE APPROACH

The final target is the research and the determination of reliable correlation between rock physic characteristics of the fractures and their nature, attitude and productivity. To this purpose, a fundamental tool of analysis is the acquisition of geophysical, temperature and pressure (T&P) logs in a number of wells as large as possible.

Geophysical Logs

The main geophysical logs usually applied in the deep geothermal exploration in Italy are listed here below together with their diagnostic aim.

- ***Gamma Ray (GR) Spectralog*** - can be performed also in cased holes and allows a detailed stratigraphic reconstruction for the entire depth of the well, even in case of cuttings absence due to Total Loss of Circulation (TLC).
- ***Densilog & Acoustilog*** - contribute to the stratigraphic-structural reconstruction of the well and are essential for the bulk density and seismic wave velocity determination in order to give calibration elements for the interpretation of surface gravimetric and seismic surveys. Furthermore these logs are fundamental to compute the formational elastic parameters and their variations in case of presence of fractures.
- ***Multi-arm Caliper –*** is very useful not only for the imaging of the hole geometry, but also for structural reconstruction by means of break-out analyses.
- ***Borehole Imaging Log –*** allows the 360° mapping of the walls of the hole by analyzing the formational variation of both velocity and resistivity. This is the only, specific tool for the direct fracture analyses in terms of nature and geometric parameters.

Usually, during the field recording phase it is possible to make a preliminary individuation of levels which can be potentially fractured. These are very often associated to:

- ➢ sharp decrease of bulk density and P wave velocity (V_P);
- ➢ strong attenuation of the wave form (WF);
- ➢ intense and very thin cavings in the walls of the hole;
- ➢ peaks of GR in case of mineralized fractures.

On the basis of this preliminary individuation, the levels to be investigated with borehole imaging log can be selected. Recently, the Circumferential Borehole Imaging Log (CBIL), based on the digital acoustic imaging technology (McDouglas and Howard, 1989), has became the most commonly used tool in Italy for the fracture investigation of deep geothermal wells. All the processing steps are mainly aimed at pointing out all those variations of the rock physic characteristics that can be related to the presence of fracture systems.

The first processing phase involve the Densilog and Acoustilog (Fig. 2) in order to compute the Acoustic Impedance, the Reflection Coefficient and the Synthetic Seismogram. The last one is particularly useful for a comparison with surface and well seismic profiles data because seismic reflections have been proved to be very often a signature of fractured horizons.

The WF analysis, recorded by means of advanced digital acoustic tool, allows to map the image of the instantaneous amplitude. This shows the WF energy distribution and content evidencing very clearly WF attenuation due to fractures. Furthermore the S wave velocity (V_S) and of the V_P/V_S ratio are also computed from the WF analyses. These parameters are combined with the density values and many elastic properties can be computed (see Fig. 2). Among these elastic parameters the Fracture Toughness Modulus is particularly sensitive to the presence of fractured levels.

The second processing phase (Fig. 3) is aimed at the fracture characterization of both the nature and the structural pattern using data from Multi-arms Caliper and CBIL (orientation-corrected in case of deviated wells).

Rough structural information comes from the break-out analysis of the Multi-arms oriented Caliper that allows the definition of the minimum horizontal stress direction (σ_3) which is orthogonal to the fracture planes considering a vertical direction of the maximum stress (σ_1).

CBIL data allow detailed structural reconstruction. In the CBIL tool an acoustic transducer, continuously spinning on the 360° of the walls of the hole, emits an acoustic pulse directed into the formation and records both the amplitude and the travel-time of the returning wave. The acoustic amplitude is mainly a function of the acoustic impedance of the formation, so that fractures and their nature (open, mineralized, foliation etc.) can be clearly evidenced.

Advanced CBIL processing techniques provide enhanced 360° acoustic amplitude images of the reflected wave. On this images it is possible to

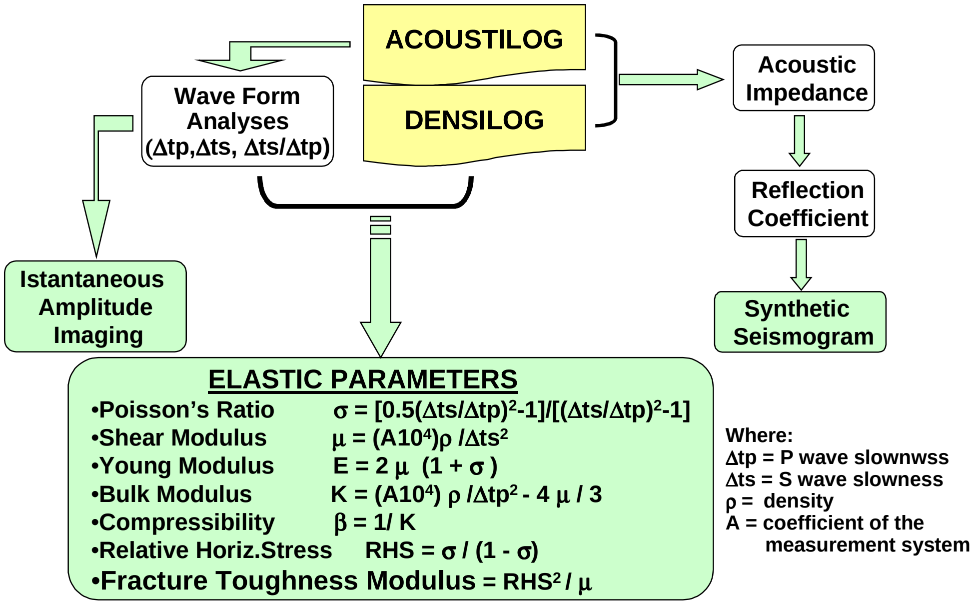

Fig. 2 – Processing Flow Chart of Density and Acoustic Well logging data

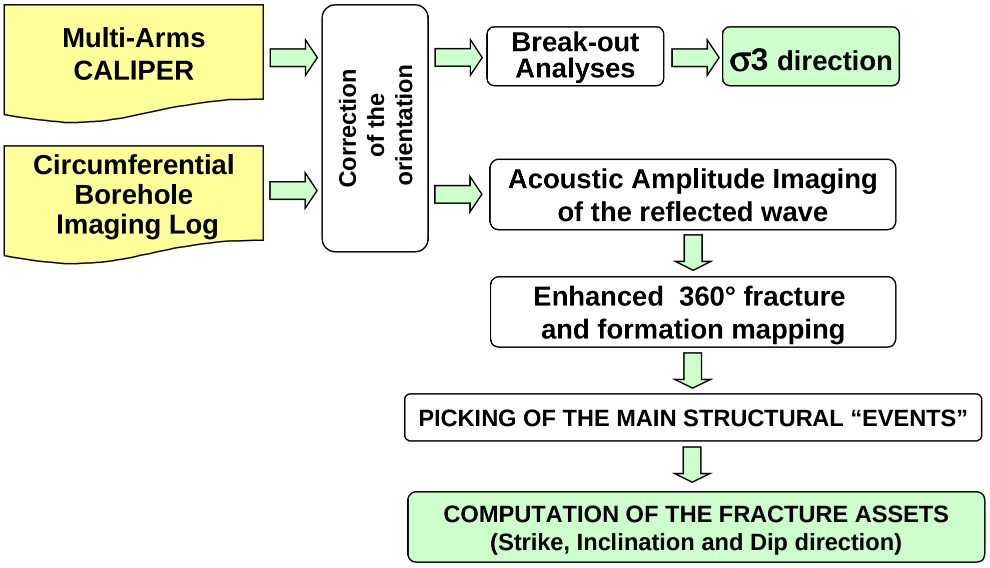

Fig. 3 – Processing Flow Chart for Fracture analyses from Well logging

distinguish different types of fractures as a function both of the acoustic impedance variation degree and of their shape and size.

These "structural events" can be than picked and all the geometric parameters (i.e. strike, inclination and dip direction) computed.

Well Testing

Temperature and pressure log

The most effective physical log measured during drilling, or immediately after well completion is the temperature and pressure one. Enel Green Power laboratories operates in the sector of research and testing using very high tech instrumentation, with a real-time acquisition. In order to operate in the conditions prevailing in the geothermal environment, most of the instrumentation, not commercially available has been especially designed and constructed utilizing innovative technologies. The specific temperature and pressure probe has the following operational limits: 316°C (extreme conditions 400°C) ± 0.2°C and 50 MPa ± 0.3%.

The utilization of T&P log can be a useful tool for the identification of each productive zone in the well and for the direct measurement of the injectivity. The overall injectivity value, measured during an injection test, can be biased by the existence of different fractures inside the well: the correct way of measuring it is to know the individual injection rate for each fracture, and the effective flowing pressure at the different vertical positions. The temperature profile during an injection test will exhibit a change of slope of the thermal gradient where there is a change in the flow rate, i.e. where there is an adsorbing zone: the thermal gradient is proportional to the fluid which passes in the formation.

Drawdown/Injection and interference

The main properties of a reservoir rock are the permeability and the porosity. The first is the rock capability of permitting fluid motion when a pressure difference driving force is applied, the second is given by the total amount of vacuum inside the reservoir, which is the storage of the fluid. The permeability distribution of the reservoir must provide a hydraulic connection throughout all the system; a pressure change in a part of the reservoir (due to exploitation or injection) is propagated in all the system. The propagation velocity of the pressure wave depends on the so-called "hydraulical diffusivity". The well testing is the way for measuring the most important reservoir parameters, as well as the characteristics of the fluid motion (Chierici, 1994)

During the drawdown/injection tests the pressure gauge is placed close to the productive zone, and the pressure change is recorded while the well is operated at constant production/injection rate. From the shape of the curve it is possible to identify the reservoir's unique characteristics: the trasmissivity (the permeability-reservoir height product), the skin factor (the well-reservoir coupling factor), the deviation from the ideal radial flow (storage effects, closed or constant pressure boundaries, linear motion of the fluid along preferential paths).

During an interference test the pressure change a given well is recorded, while a drawdown/injection test of another one is performed (Grant et al, 1982).

This is a very important way for measuring the average characteristics of the reservoir in the volume between the two wells, or for establishing a higher limit of the permeability in the case of negative response.

WELL SESTA 6 BIS A: EXPERIMENTAL DATA

The deviated well Sesta 6 bis A was drilled in the northern area of the Larderello-Travale geothermal field, in the same site of the vertical well Sesta 6 bis (see Fig. 1). The latter had reached productive levels at depth higher than 2400 m, in correspondence of a seismic reflection marker inside the metamorphic basement, but no geophysical logs for fracture characterization had been performed.

In order to investigate and characterize the fractured zones encountered during the drilling of Sesta 6 bis A well, the following set of geophysical logs was performed (Table 1):

Log	Depth Interval (m)	Notes
GR-Spectralog	0 – 3934	0 –2196 in cased hole
Densilog	2195-3934	In open hole
Acoustilog with WF		
4-Arm Caliper		

Table 1: Performed geophysical logs in the well Sesta 6 bis A

A set of six intervals for CBIL investigation were identified by means of the preliminary field fracture detection as follow (Table 2):

Log	Depth Interval (m)
CBIL	2550-2750
	2820-2890
	2915-2975
	3180-3210
	3380-3410
	3740-3780

Table 2: Performed CBIL investigation.

Rock Physic

The standard processing of the geophysical logs contributed to the stratigraphy reconstruction, although the well was drilled for a large depth interval in TLC (from 2600 m to the bottom of the well, 4000 m), and allowed to determine the main rock physical properties for each investigated geological formation. The following table 3 gives an example of geological characterization performed by means of the GR Spectralog, which gives a value of total GR and of its spectral components: Potassium (K), Thorium (TH) and Uranium (U).

Lithology	Depth Interval (m)	GR (GAPI)	K (%)	TH (ppm)	U (ppm)
Neogene Sediments	*0-280*	44.0 ±3.8	1.1 ±0.1	3.9 ±0.6	2.0 ±0.5
Flysch	*280-550*	63.0 ±5.3	1.9 ±0.1	2.8 ±0.77	2.8 ±0.7
Tectonic Wedges	*550–1900)*	48.0 ±7.6	1.92 ±0.1	6.7 ±1.2	2.5 ±0.7
Phyllites	*1900-2220*	93.5 ±12.5	2.38 ±0.6	11.7 ±1.9	3.2 ±1.1
Micaschists	*2220-3800*	109.8 ±35.5	2.40 ±0.9	12.7 ±4.6	4.4 ±1.6
Gneiss	*3800-4000*	N/A	N/A	N/A	N/A

Table 3: Geological characterization from GR Spectralog.

For the micaschists, the investigation by means of many geophysical tools made available further rock physic information (Table 4):

Parameter	Value
V_P	4.87 ± 0.32 (km/s)
V_S	2.81 ± 0.20 (km/s)
V_P/ V_S	1.7 ± 0.1
Density	2.77 ± 0.07 (g/cm^3)
Acoust. Imp.	12.7 ± 1.6 (kmsec^{-1}gcm^{-3})
Young Mod.	53.25 ± 10.2 (GPa)
Poisson Coef.	0.2 ± 0.06
Fract. Toughn.	0.006 (GPa^{-1})

Table 4: Advanced rock physic information for the micaschists interval.

Two core samplings have been analyzed in the TLC interval, in order to have a direct measurement of the relevant rock physics and geological data. In table 5 the petrophysical information from the two cores (the first in the micaschists and the second in the gneiss stratigraphic zones) are presented. The bulk density of 2.6 g/cm^3 can be compared with the previous indirect measurement from geophysical logs of 2.77 g/cm^3 for the micaschists reservoir rock.

Core sample	Depth Interval (m)	Grain density (g/cm^3)	Bulk density (g/cm^3)	Porosity (%)	Heat capacity (J/g°C)
Micaschists	3085-3088	3.0	2.6	1.3	0.67
Gneiss	3830-3833	2.9	2.6	1.6	0.67

Table 5: Core samples petrophysical determinations in the deep TLC drilling zones.

Well testing

During the well drilling (8 May 2000-12 September 2000) many adsorbing zones have been detected, at 818 m and 1618 m; these low productive zones have been covered with the casing. The open hole zone begins at 2202 m.

The first important fractured zone has been highlighted at 2600 m; after acidification and hydraulic stimulation an injection test measured a low injectivity: 1.6 m^3/h/bar. Subsequently, a T&P log has been recorded during another stimulation (with 80 kg/s for 2 ½ hours), followed by another medium-duration injection test (with 8 kg/s). Three adsorbing zones have been identified, but, due to the low overall injectivity, it was decided to deepen the well, until the final depth of 4002 m was reached. The following tests have been performed:

- Build up immediately after drilling;
- A 17 days production test (the well production could be estimated as 4 kg/s at 1.6 MPa well-head pressure);
- Two T&P logs during the production test, with an indication of six productive fractured zones (Fig. 4);
- An interference test (pressure on Sesta 6 bis), showing a linear motion connecting the two wells;
- Final build up after production test.

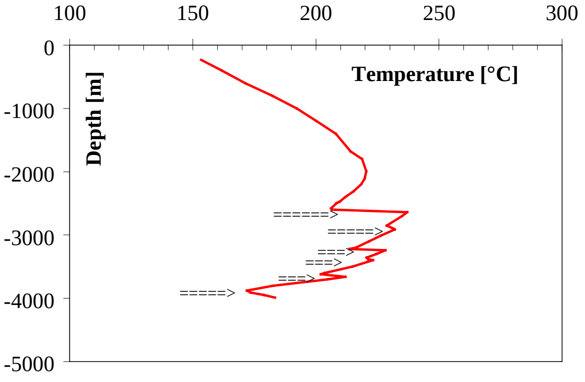

Fig. 4 Temperature dynamic log after production test, showing the fractured zones as change of slope in thermal gradient.

Unfortunately, the drawdown analysis does not give a clear indication of the reservoir characteristics, due to the superposition effects of each production zone.

The final build-up shows a slight tendency toward a radial motion, with a stabilized flow rate of 2.2 kg/s at 1.6 MPa. Assuming 1000 m of reservoir height, the formation permeability can be estimated as 0.7 mD and a negative skin factor of –4.2.

The final list of the fractures is given in Table 6.

Depth (m)	First T&P Flow rate (kg/s)	Second T&P Flow rate (kg/s)
2640	2.08	1.77
2910	1.11	0.14
3240	N/A	0.33
3400	N/A	0.14
3660	N/A	0.33
3880	2.31	1.44
TOTAL	**5.50**	**4.15**

Table 6: Fractures determined by T&P log during production test.

Fracture identification

The geophysical log processing confirmed that the six depth intervals preliminary identified for the CBIL investigation were particularly affected by signatures related to the presence of fractures (Fig. 5).

The CBIL analysis allowed the identification of different kinds of fractures and their geometrical parameters (Fig. 6). These last were processed and mapped for each interval as "pole density of all the fracture planes", using the Wulf's lower hemisphere stereo-graphical projection.

For each interval the pole density distribution, for fractures and faults only (foliations excluded), is shown in Fig. 7 together with the most representative cycle-graphical traces. These are characterized by a prevalent E-W azimuth direction, the dip direction is almost variable, but the inclination shows a tight variation between 65 and 80°.

A comparison with core fracture analysis is possible only for cores extracted from the same metamorphic formation in the vertical well Sesta 6 bis. They are not oriented, so that the only reliable value is an average slope of about 70° measured on few samples of continuous joints.

A comparison between the fractures detected by geophysical logs and well testings is given in table 7 together with a tentative correlation between fracture asset and productivity.

There is quite a correspondence with fractures detected by well testing in four out of six intervals characterized by geophysical fracture signatures.

Excluding the deepest productive zone at 3880 m, not investigated by CBIL, the levels with higher productivity (1.77 and 0.33 kg/s) are associated with sub-vertical fractures (inclination of 70-87°) with a E-W strike direction and Northward dip direction.

Fractured levels from CBIL				**Fractures from Well Testing**	
Depth (m)	*Strike Direction*	*Slope and dip direction*	*Number of Samples*	*Depth (m)*	*Production Flow rate (kg/s)*
2550-2750	E-W	87° N	242	2640	1.77
2820-2890	E-W	84° SE	72	Not detected	
	NNW-SSE	46° E	22		
	N-S	50° W	22		
2915-2975	N-S	27° E	36	2910	0.14
3180-3210	E-W	70° N	18	3240	0.33
3380-3410	WSW-ENE	24° SSE	30	3400	0.14
				3660	0.33
3730-3780	Not definable		few	Not detected	
---***Bottom Log***---					
				3880	1.44

Table 7: A comparison between the fractures detected by geophysical logs and well testing.

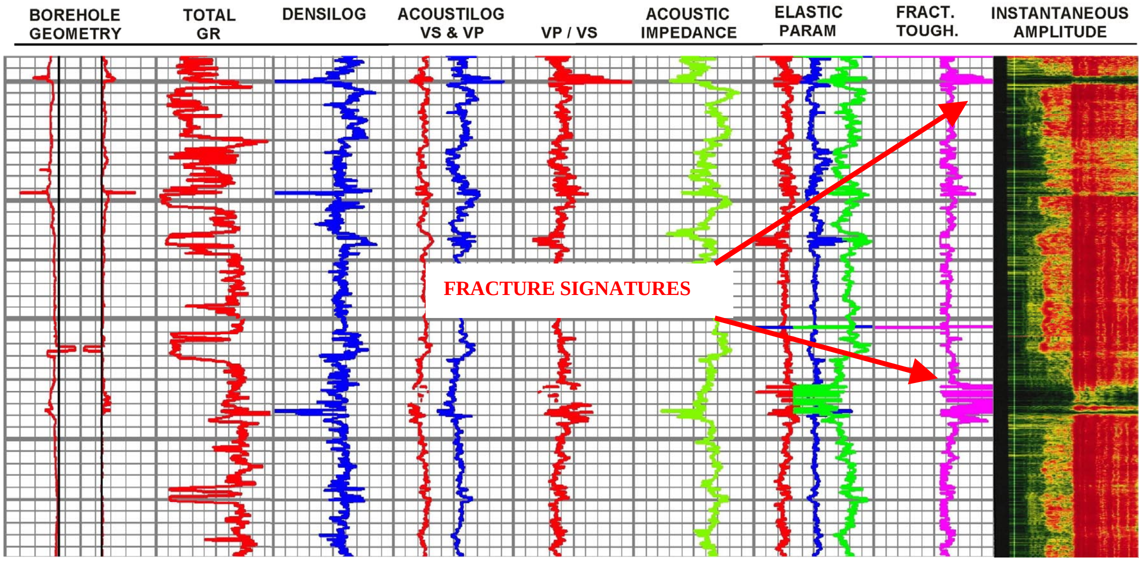

Fig. 5 – Fracture signatures from geophysical logs

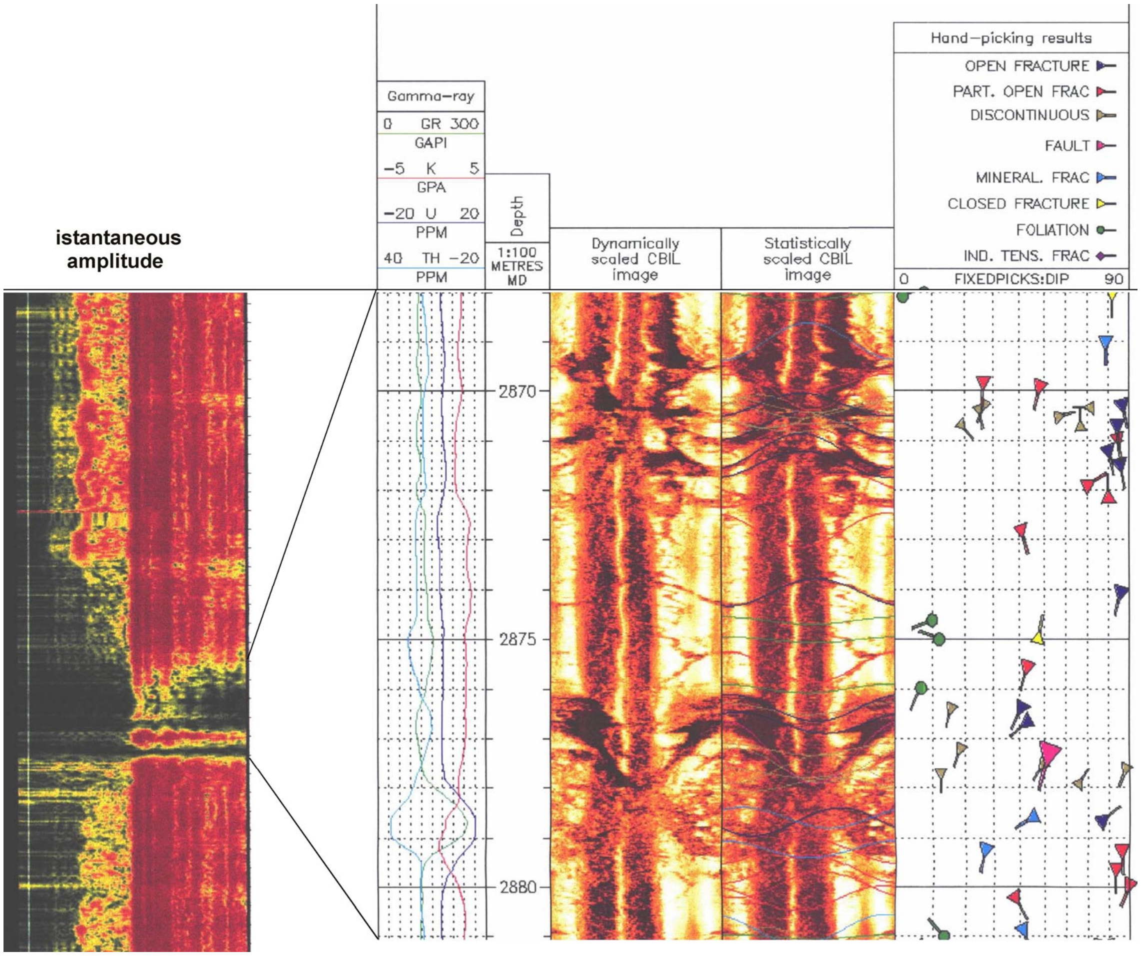

Fig. 6 – Fracture analysis from CBIL

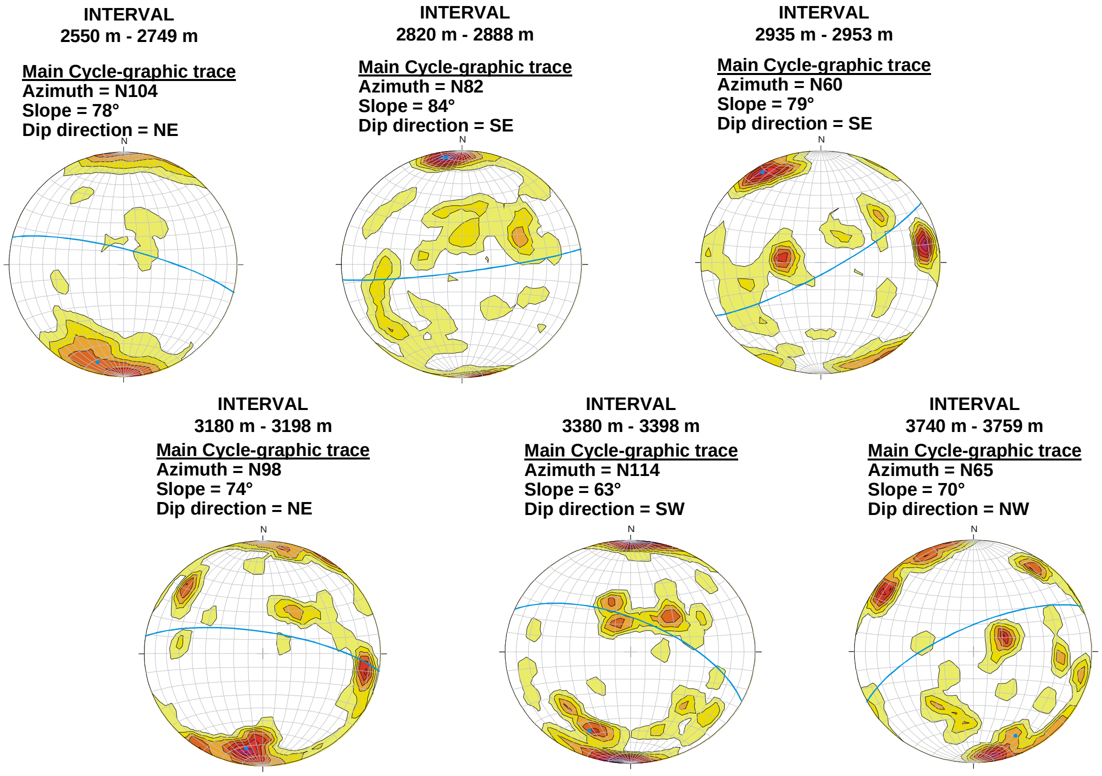

Fig. 7 – Fracture asset mapped as "pole density"

CONCLUSION

In a deep geothermal well of the Larderello-Travale area (Sesta 6 bis A, about 4000 m deep) a complete set of geophysical logs was collected, in order to compare and chaacterize the fractured zones identified with the standard well-testing procedures. In particular, the CBIL method, used in conjunction with other techniques, proved as very effective and detailed for a clear signature of the fractures already tagged by standard well testing procedures.

Unfortunately, one of the most important productive zone (at 3880 m) was not investigated by the geophysical logs. Four of the six intervals characterized by geophysical fracture signatures, have a good correspondence with fractures detected by well testing.

The higher productivity zones (1.77 and 0.33 kg/s, at 2640 m and 3240 m respectively) are in association with sub-vertical fractures (inclination of 70-87°) with a E-W strike direction and Northward dip direction. These results should be considered as preliminary: further experimental verifications will be achieved in the near future.

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