ENEL'S EXPERIENCE WITH DIRECTIONAL GEOTHERMAL WELLS

Fabrizio Bianchi[1], Cesare Quintavalle[2], Michele Rossi[2]

[1]ENEL S.p.A. DPT/VDT/G, Via Andrea Pisano 120,56122 Pisa, (Italy)
[2]ENEL S.p.A.,DPT/VDT/G/Unità Perforazioni, 56044 Larderello, (Italy)

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ABSTRACT

This paper describes the experience gained by ENEL in drilling directional geothermal wells over the last ten years.
Besides describing the major problems that were faced and the technological improvements that were achieved, the paper illustrates two special applications of directional drilling technology: the realization of the horizontal well Lamarello 1A and the forked well Padule *2.*
Further development of directional drilling to exploit deep geothermal horizons requires that the industry of this sector develop mud motors and MWD instruments suitable for extended use at high temperatures.

1. INTRODUCTION

In 1979 ENEL began a deep drilling program aimed at exploring Triassic and Paleozoic formations lying above 4000 m depth in order to ascertain whether geothermal fluids could be found in them.
The existence of new productive horizons was also suggested by the results of seismic measurements.
Vertically dnlled research wells confirmed the presence of geothermal fluids between 3000 and 3500 m depth.
A section of the typical formations crossed is presented in Fig. 1.

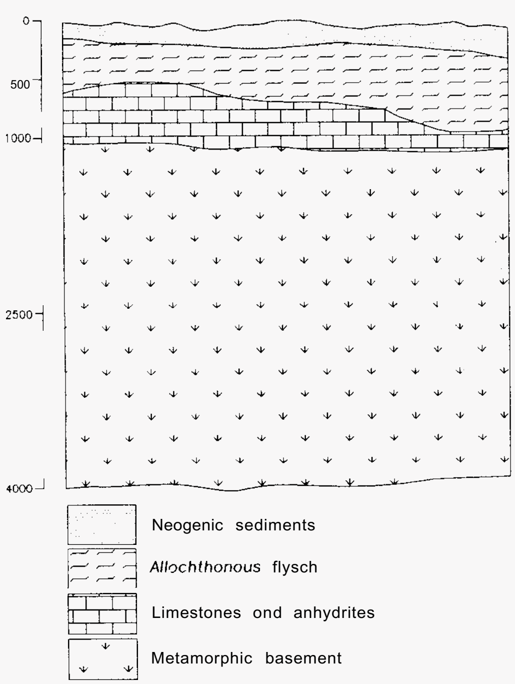


Fig 1. – Schematic geologic cross section of Larderello geothermal fields

The discovery of this "deep" reservoir was of great interest because of the higher enthalpy of the fluids in it compared with those of the shallow reservoir. This stimulated ENEL to work toward new industrial exploitation by developing new methods and utilizing commercially available state-of-the-art technologies.
The fist application of directional well technology to exploit the deep reservoir was in 1983 in the Amiata development project.
The 14 directional wells drilled represented the necessary trial in order to ready these specific geothermal techniques for future applications. The fist working hypothesis was based on the possibility of lowering the mud motor operating temperature thanks to the presence of lost circulation zones. As shown in Fig. *2,* the well profile was done in four phases:

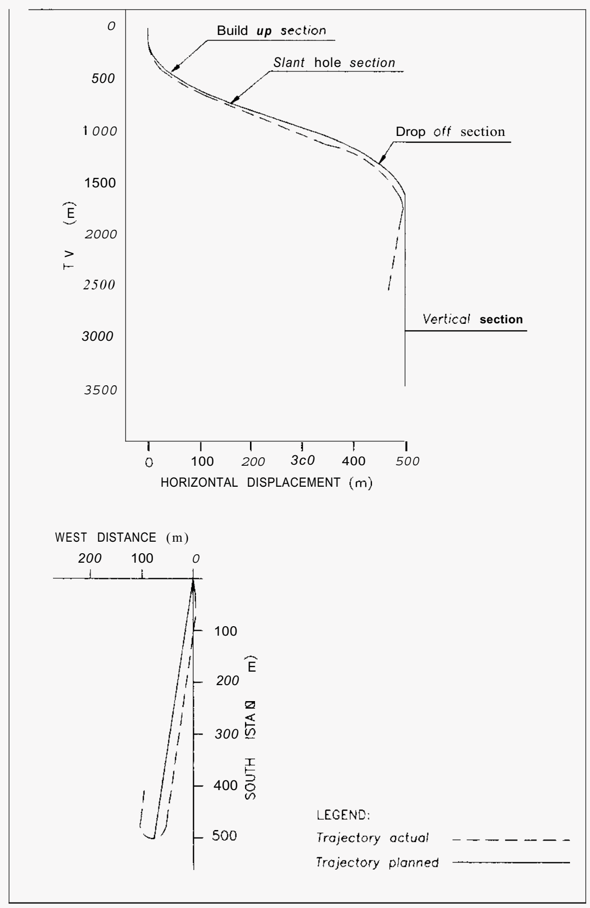


Fig. 2 – Well path PC 35 A

- the first phase, for the construction of the "vertical portion" to 150 m;

- the second, for realizing the "build-up" section, which was then kept at a constant angle of 31" to a depth of 1030 m. This portion should be mostly in formations of the anhydritic series type, almost always characterized by circulation losses:
- the third "drop-off phase" by decreasing the angle of inclination to the vertical, was to have reached the maximum planned horizontal displacement of *500* m;
- the fourth phase envisaged "vertical drilling" of the basement to the final vertical depth of 3500 m.

The above project was implemented by drilling well PC 35 A. The first two phases were drilled according to plan without any serious problems. However, in the third phase it was not possible, despite drilling with pendular drill strings, to decrease the inclination angle below 4°, leading to an additional increase in horizontal displacement. In the end this increase proved to be negative due to the strong variation of azimuth (see Fig. 2).

Hence, this first experience evidenced the phenomenon of spontaneous deviation in drilling the basement at low angles of inclination. Subsequent experiences demonstrated that this variation is less in correspondence to greater inclination angles.

In addition, the well axis rotation caused an anomalous increase of the friction on the drilling assembly so as to preclude reaching the planned target. In spite of this, well PC 35 A, depth 2460 m, turned out to be productive.

This experience suggested modifying the profile of the next "slanted well" so as to drill the basement at high angles of inclination in order to reduce or nullify the effect of spontaneous azimuth deviation. The slant profile involved positioning the KOP at greater depths and consequently at higher temperatures. The high formation temperatures and the absence of absorbing zones to permit cooling led ENEL to attempt using completely metallic turbines made by various suppliers.

The high turning speed of such turbines (from 700 to 1200 rpm) allowed the use of tricone bits for only five to seven hours, an insufficient period of time for definition of the KOP or azimuth corrections. Diamond bits were therefore used.

However, it immediately became clear that the turbines' low torque did not allow loading the bit with weights over 4000 kg; the result was frequent stalls and very low drilling rates. In suitable thermal conditions, the best performances were achieved with mud motors and conventional bits.

2. ENEL'S EXPERIENCE IN DIRECTIONAL DRILLING

Since the experiments in the Amiata field, new reservoir exploitation has been carried out by means of directional drilling, which has become increasingly important: nowadays over 70% of the wells drilled by ENEL are directional.

Average well depths range fi-om 3000 to 4000 m, but a few wells have been drilled deeper than 4000 m (for example, Radicondoli 26 B, depth 4604 m).

The standard profile of a directional well is planned as follows:
- KOP at about 1000 m depth
- maximum inclination angle 25"
- dlsplacement of about 1000 m at a vertical depth of 3500 m, as shown in Fig. 3.

The exploitation projects for deep horizons call for drilling groups of three wells from the same location, two of them directional. In one exceptional case five wells (four directional) were drilled from the same site.

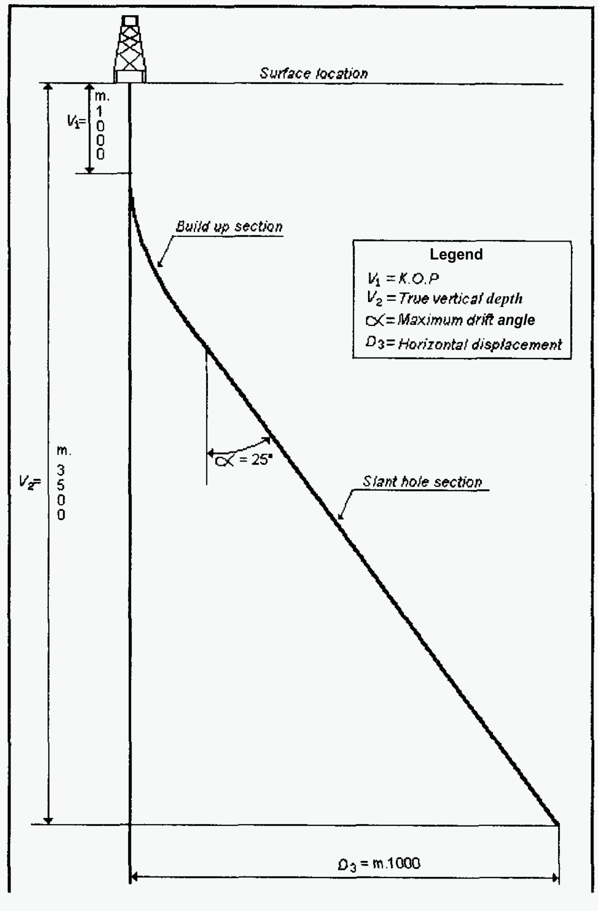
The translation of the completely assembled equipment, on the site itself, is achieved by means of a system designed by ENEL that makes use of hydraulic pistons.

The problems encountered during directional drilling can be either thermal or mechanical in nature.

The thermal problems originate from the temperature of the formations penetrated by the dnlling. The thermal gradient is on the order of 2.5°C/10 m (and higher), so in the well's thermal equilibrium conditions, at 600 m depth a temperature of approximately 150°C is already reached, which represents the operational limit for the mud motors and measuring instruments (MWD and steering tool).

In order to increase the utilization depth of the equipment it is important to cool the well by means of fluid circulation. However, the well cooling is more effective with lost circulation.

When this condition occurs, which is frequently the case in our geothermal fields, the thermally accessible area deepens, reaching equipment utilization depths greater than 3000 m. Indeed, it has been possible to cany out side track operations in deep wells when lost circulation conditions occur.



Fg 3 - *Typical trajectory (vertical sectmn)*

Mechanical problems manifest themselves via two different phenomena: friction and spontaneous deviation.

Spontaneous deviation causes great irregularity in the azimuth and inclination of the well axis. This happens both in the cover formations and in the schistose quartziferous basement.

To solve the problem with regard to the cover formations, ENEL tried turbodnlling with the "steerable system". The use of this system should have guaranteed perfectly vertical drilling until the KOP was reached, at the same time also providing better and faster definition of the bending according to the planned direction.

After much testing, the "steerable system", which is widely used in the oil industry, proved to be ineffective, mainly in the "sliding mode" utilization phase due to frequent dnll string jamming, low penetration rate, and above all lack of correction of the well axis.

It is thought that the lack of success of the "steerable system" is due to the high resistance exerted by the formation on the drill string, in the affected formations. It bears mentioning that ENEL tried systems of this type from three different manufacturers.

The phenomenon of spontaneous deviation can prove to be quite significant when dnlling in fractured areas of the basement. Directional drilling operations performed in other areas, such as those of Latium, also in schistose formations but not such as to cause large spontaneous deviations, have not been affected by any difficulties of a mechanical nature.

In order to find a solution to the problem of spontaneous deviation in the schistose quartziferous basement, ENEL chose a direction leading towards better comprehension of the causes of the natural deviation phenomenon. The first observations performed on rock samples confirmed this thesis. Moreover, an interesting correlation has been established between the spontaneous trend of the wells and mean lay of the schistosity planes. Its measurements have been made by means of a Dip Meter Log*. a Formation Micro Scanner Log* and oriented core samples. In order to gain greater insight, a research project is being set up to determine and possibly quantify the influence of the various parameters.

While awating a scientific solution to the problem of spontaneous deviation, since the main concern is reaching the target, an essentially practical approach is used which consists in optimizing the site choice as much as possible, making this choice dependent on the well's target and not the contrary. In other words, once the target has been set, that is, the position of the weilbottom has been decided, one has to search for the best path to reach it.

The construction technique is based on the assumption of substantial uniformity of the mechanical characteristics of the metamorphic formations in the areas where the groups of three wells are located.

The first of the planned series in each location, usually the "vertical" one. is used as "pilot well" to characterize the formation. Fig. **4** shows how strong the deep formation's tendency to cause spontaneous deviation is. The next target is then defined based on the prediction that can be obtained from the analysis of the data relating to the pilot well construction.

Such data analysis, performed on a computer, is based on predictions about the path of the directional wells belonging to the same group. It is obtained by assigning to each depth value the corresponding spontaneous azimuth deviation and the increase of the inclination angle according to different possible angular increment programs. Among the various curves thus obtained, it is possible to select the one believed optimal for the projected aim of each directional well. In spite of the limits of the hypothesis of uniformity of formation characteristics and the difficulties of precisely quantifying the evolution of the spontaneous deviation phenomenon. significant results have been obtained.

The examples shown in Fig. 4 refer to the exploitation of deep horizons by drilling three wells from each site.

To solve the mechanical problems, two different techniques were considered.

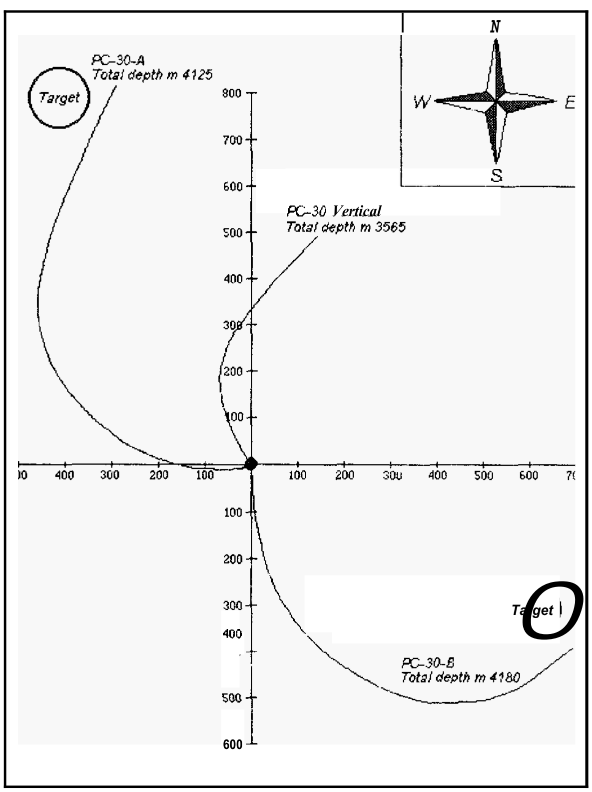


Fig. 4 - *Wells trajectory (Horizontal section)*

* Dip Meter Log and Formation Micro Scanner Log are trade marks of Schlumberger Intl.

The first was aimed at minimizing the friction exerted on the formation by the drilling assembly by modifying the dnlling fluid with the addition of friction reducers.

In recent years, in conditions of partial or total lost circulation, the use of *air* as circulating fluid has been tried to spread directional drilling.

On the one hand, the air makes possible to continuously test the formation, but this involves strong friction on the drill suing that can jeopardize the attainment of deep targets.

To reduce friction various fnction reducers, constantly added to the air, have been tried.

After various tests a light fluid composed of a mixture of air, water, foam and fnction reducers was tuned up.

This new drilling technology keeps the circulation temperature close to the formation's stabilized temperature (temperatures over 300°C). This has required modifying the standard heat shields for the instruments that measure inclination and direction, improving their insulation capacity by introducing new materials with low thermal conductivity (cellular glass) to make them suitable for use at such temperatures.

The second was the introduction of an intermediate liner, with a shoe between 2000 and 3000 m and the liner hanger just inside the shoe of the last casing (1000-1500 m).

Friction and spontaneous deviation also have negative effects on the casing, which is subjected to intense wear and tear.

For this purpose, non-rotating protective shields of soft metal have been designed and used with success (see Fig. *5).* They are assembled on the dnll pipes and located in the areas that are most worn.

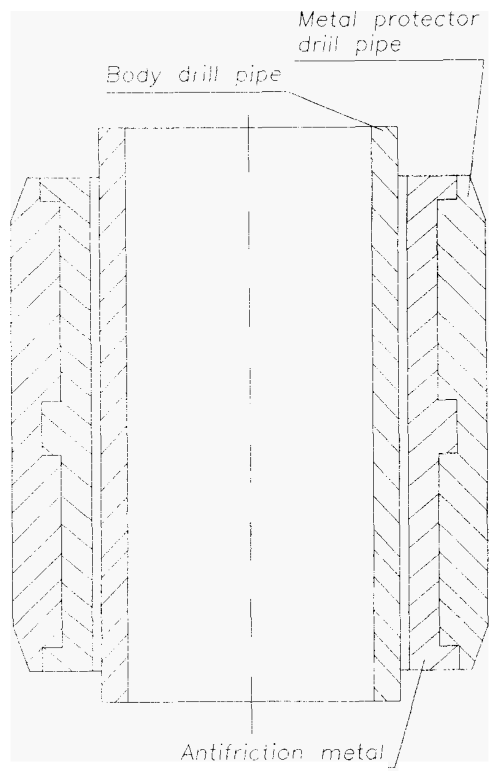


Fig. 5 – No rotating metal drill pipe protector cross section

3. SPECIAL APPLICATIONS OF DIRECTIONAL DRILLING TECHNOLOGY

A unique and very important aspect of directional drilling technology has been the drilling of a horizontal well, Lamarello 1A, realized in 1990.

The horizontal drilling was planned with the aim of verifying and evaluating the applicability of this method in a high temperature, steam-dominated geothermal reservoir like the one at Larderello.
This experience was the first ever in a high enthalpy geothermal system. The method had been previously applied in a low temperature, water-dominated system.
The special feature of these drillings is achieving better production performance since a greater number of subvertical productive fractures should be crossed.
The primary goal of well Lamarello 1A was horizontal drilling of a higher permeability layer in a better direction for intercepting a subvertical fracture system oriented in an approximately NW-SE direction. The main characteristics planned for this well, in accordance with the foregoing, were:
1) well orientation: S 70° **W**
2) depth of reservoir top about 700 m
3) tangency depth of the horizontal dnlling section around 820 m
4) length of horizontal tract about 350 m
The horizontal drilling was carried out making use of special equipment as, mud motors, MWD, Telepilot, etc., and did not encounter any operative difficulty since the well was in lost circulation and therefore cooled.
Because of the temperature **limits** (~ 150° C) **of** the necessary equipment the technology used here cannot be advised for drilling very deep horizontal wells, for which it would be especially useful.
The horizontal well Lamarello 1A intersected the shallow reservoir in a horizontal plane for about 400 m, as shown in Fig. 6.
Only two fractures were discovered at 915 and 1250 m depth, corresponding to 786 and 807 m on the vertical, so the well's production was modest, around 10,000 kg/h.

	Measured depth (m)	Vertical depth (m)	Horizontal displacement (m)
N° 1 Planned trajectory	1397	819	824
N° 2 Real trajectory	1425	804	825

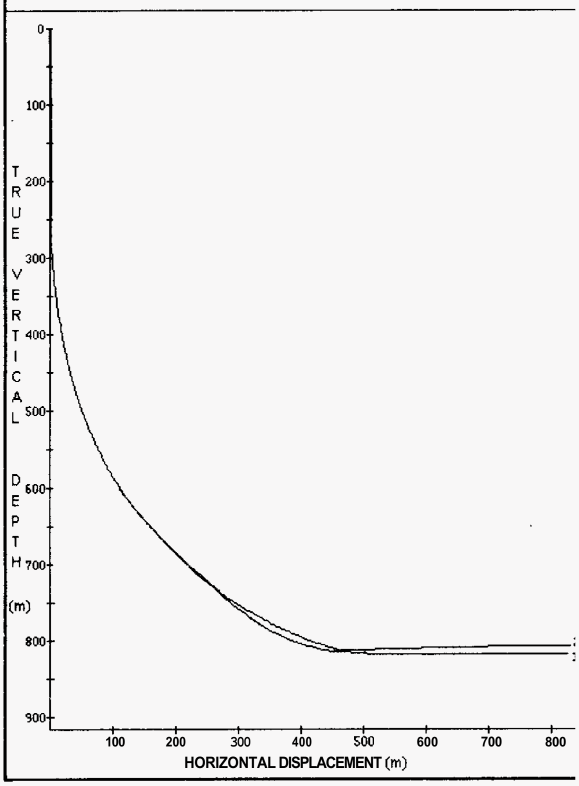


Fig 6 - *Well trajectory of the horizontal well Lamarello 1A (vertical section)*

In the final analysis, the dnlling of horizontal well Lamarello 1A demonstrated the feasibility of this operating methodology in the field of geothermics, even though the production results were not satisfactory because a sufficiently high number of productive fractures were not crossed.
A further positive experience in the field of directional drilling is represented by the realization of the first European forked geothermal well.
The drilling of the forked well Padule 2, carried out by ENEL, confirmed the validity of a new technology developed over the last few years. To realize its first forked well, ENEL chose the Padule **2** hole, which displayed low productivity and therefore, in the case of failure, represented an acceptable economic loss.
The forked well Padule 2 is made up of a first vertical branch dnlled to a depth of 3703 m from which a second directional branch kicks off at a depth of 1273 m, with a displacement of about 110 m from the vertical, as shown in Fig. 7. The technology applied in constructing the forked well involves the use of compressed air. This enabled evaluation of the production increase at the reopening of the first branch.
The second branch was drilled from a casing window of only 8 m, making it easier to reenter in the original branch.
The re-enuy drilling assembly included:
- mill tooth bit diam. 12 1/4"
- crossover M/F 6 5/8" REG with float valve
- crossover M/F 6 5/8" - F 7 5/8" REG
- two 11 3/4" drill collars

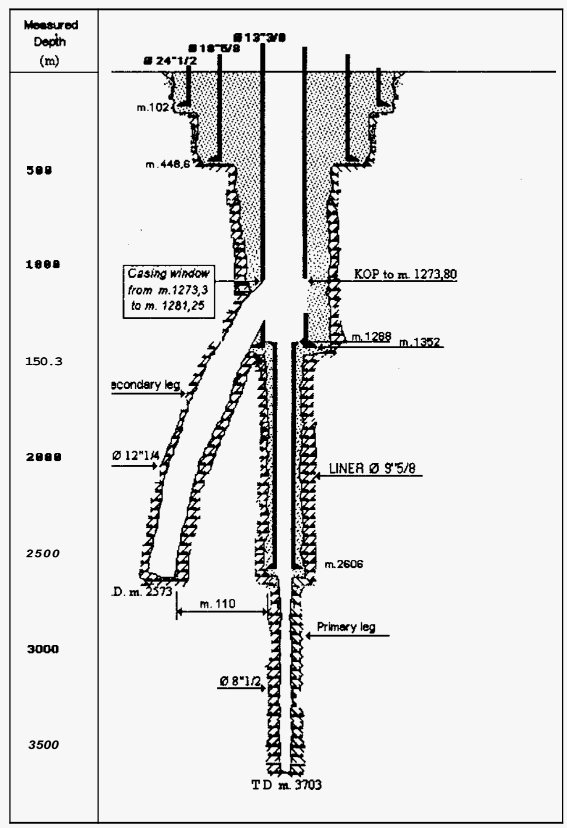


FIG 7. *Well Padule 2-forked (Vertical profile)*

The first branch of well Padule 2 has a productivity of 10,000 kg/h of steam. The drilling of the second branch brought a steam production of 4400 kg/h.
After the reopening of the first branch overall production was around 10,000 kg/h, or nearly equal to that of the first branch alone even tough the steam was at higher pressure. Hence, despite the wellbottoms of the branches being at different depths and therefore not interfering with each other, the result was not the the sum of the two steam flows, likely due to permeability damage of the first branch.

In this case too the outcome must be considered positive since it contributed to improved forked well drilling technology, which **may** be of interest for further applications in development fields, especially when one considers that the second branch was drilled at much lower cost.

4. CONCLUSIONS

Directional well drilling has been widely used by ENEL in drilling geothermal wells, chiefly in development projects, since the first experiments in the early 1980s. Currently directional wells represent some 70% of all development wells.

Over the years much experience has been gained and several important technical problems have been tackled and for the most part solved. Among them we can cite:

- optimum directional well profile: profiles have been identified that increase the chance of attaining the objective in relation to the formations crossed;
- spontaneous deviation: much work has been done to gain greater insight into the phenomenon and measures capable of limiting it;
- decrease of friction on the drill string;
- identifying a wide range of drilling fluids that are also suitable for duectional drilling;
- development of metal protectors for casings and high temperature heat shields for single shot surveys.

At present important limitations still exist due to the lack of appropriate equipment, above all mud motors and MWD instrumentation for well axis correction or for realizing side tracks in temperature conditions in at least the 150-250°C range, which could enable additional evolutions in well profiles.

As a further confirmation of the maturity of the new technologies, ENEL has drilled the horizontal well Lamarello 1A, the first of its kind in the world, and the forked well Padule 2, the first in Europe.

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