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Analog VSP tools operated in High Temperature wells using gimbal mounted 3C geophones and a hydrophone, for fractured reservoir characterization such as Soultz

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VSP operations in the deep GPK-3 and GPK-4 low deviation wells of Soultz-sous-Forêts, Alsace, Eastern France, required downhole tools to be able to sustain temperatures as high as 195˚C for several hours. The temperature range in the deep reservoir interval, 4 to 5km deep, increases linearly from 170˚C to 200˚C.

The characterization of the faults and fractures in the 4500m to 5000m deep geothermal reservoir led the Soultz-EEIG managers to express the following downhole VSP tool requirements:

- Orientation device (s) for the 3C geophones at high temperatures and orientation precision. As the well deviation in the targeted depth intervals of VSP measurement is mostly higher than 10˚, a gimballed geophone mounting was chosen for the 3C geophones with a ‘trunnion’ arrangement. This means one rotation axis coincides with the VSP tool axis, thus the well axis, and that the orientation of the horizontal geophone components is directly determined from the known well trajectory. Moreover, the variable well inclination allows the gimbal threshold of sensitivity to be found, above which the horizontal component

orientation is fully consistent between adjacent depth stations.

- Isotropic mechanical coupling to be as good as possible.
- Hydrophone component to be included, resulting in a four component (4C) downhole VSP tool. Hydrophone and geophone data can be analysed in combination in terms of P and S wave mode identification, and also allow better signal to noise quality in uncemented cased hole. In addition, provide the potential for permeable fractures intersecting the wellbore to be identified.
- High Temperature (180˚C-200˚C) ratings for all the mechanical and electrical components of the VSP tool and sensors.
- Reasonable field maintenance requirements for VSP tools operated everyday in harsh well environments.
- Ultra-High Temperature (220 to $>$250˚C) VSP tools might be envisaged for future VSP operations in geothermal wells, using the latest technological developments. .

Specifications and real time adjustments of the field operation

- In order to speed up the field VSP acquisition, and meet the daytime only logging operation restrictions over several days with a single field crew, the simultaneous use of two vibrator sources at each VSP tool position was planned. It was decided to locate at least one vibrator at a substantial offset distance from the VSP tool, in order to use the P-wave direct arrival energy of the offset VSP data for orienting the horizontal components in the depth intervals with very low well inclination. This uses the hypothesis that the P-wave ray is located in the vertical plane containing source and VSP receiver.
- In order to further accelerate the field operation, both wells GPK-3 and GPK-4 with wellheads on the same platform were logged at the same time. This required two cable units and two active VSP tools simultaneously, plus one spare tool, so that 4 VSP data sets were recorded in each run. A total of 13 runs were recorded successfully over 20 work days , resulting in multi offset / multi azimuth VSP operation over 52 surface source positions
- The wells to be logged did not present any difficulty in running in the tool or pulling it back out of the open hole interval, in spite of a minor shearing of the casing in one well and caving in the vicinity of the casing shoe.

- Temperature induced noise bursts from the electronics degraded the signal to noise ratio in the deepest, hottest part of the wells. This led the field engineers to compensate for it by logging during the tool's descent, together with increasing the effective vibrator source sweep duration.

For all the above, the ASR VSP tool manufactured by Avalon Sciences was chosen in combination with a HT down-hole hydrophone sub. The use of 5 VSP tools allowed the heavy 2007 VSP campaign in Soultz to be completed: moreover, innovative and unexpected seismic results in the deep hot fractured rock mass were derived.

Last, additional info and recommendations are suggested in the present paper for equipment to be used in future 3C/4C VSP surveys in similar or tougher downhole conditions.