DEVELOPMENT OF THE CSMA MARK II HIGH TEMPERATURE BOREHOLE SPARKER SOURCE

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KEY WORDS

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ABSTRACT

A downhole sparker seismic source was developed at the CSM Geothermal Energy Project for imaging between boreholes at up to 3 km depth over a range of a few hundred metres. In September 1992 a major research and development programme was instigated to increase the penetration, operating temperature range, depth range and reliability of the tool. The programme consisted of laboratory studies of the spark discharge process and re-engineering of the tool.

The upgraded tool can operate continuously at temperatures of up to 200°C for 10 hours and fire 700 times per deployment. The penetration, without stacking, has been increased from around 500 m to in excess of 850 m in granite. The performance of the tool has been established during surveys at the European HDR site at Soultz, France and from development trials at CSMA.

1 INTRODUCTION

Borehole seismic sparkers were originally developed for use in engineering applications (McCann et al., 1975) from marine sparkers used in high resolution reflection surveys. In comparison with other borehole sources such as swept frequency devices, clamped downhole hammers and borehole airguns, sparkers are relatively simple and easy to operate. They are particularly well suited to tomographic type surveys, where large numbers of source locations and shots are required, as the tools are not clamped and the shot rate is typically 2 - 10 per minute.

Sparkers generate acoustic energy when a spark is created by the rapid discharge of electrical energy between one or more pairs of electrodes immersed in an electrolyte, usually salt solution. Typical discharge voltages are 4 - 15 kV. Using a high voltage power supply and capacitors several kJ of energy can be stored and discharged in a single spark.

For surveys of up to a few hundred metres depth, the power supply and capacitors may be located at the surface and connected to the electrodes downhole by a high voltage cable. The maximum depth of this type of operation is limited by the drop in voltage along the cable, which if it falls too low prevents a spark forming. This limitation can be overcome by incorporating the high voltage power supply and capacitors in a borehole tool with the electrodes. In this case only a low voltage supply from the surface is required to power the tool.

CSM Associates Ltd (CSMA), previously the CSM geothermal energy project, have been developing downhole sparkers for 10 years for cross-hole imaging of geothermal reservoir stimulation experiments. The CSMA sparker has recently been the subject of a major research and development programme to upgrade it for use at the European Hot Dry Rock research site at Soultz in Eastern France (referred to hereafter as Soultz) (Garnish et al., 1994). In this application penetrations of the order of 750 m operating in wells at temperatures of up to 200°C and 3.5 km depth are required.

2 LABORATORY RESULTS

Prior to the development reported here, the CSMA sparker had a maximum penetration of 700 m with 10 fold stacking. However, the signal to noise ratio at the longest offsets was poor and the P wave arrival was difficult to pick. In principle the penetration could be increased simply by raising the voltage and energy discharged but these parameters could not be altered significantly without increasing the size of the tool. Due to physical constraints on the size of the sparker, imposed by the need to operate in boreholes of 6" diameter or less, this was not practical. Instead it was necessary to look at ways of improving the efficiency of the conversion of electrical to acoustic energy.

The objective of the laboratory research programme was to determine the factors which controlled the acoustic output of the sparker. In addition it was hoped to determine if the acoustic frequency could be controlled, as dramatically higher penetrations can be obtained from comparatively small reductions in frequency.

During the laboratory trials the following parameters were investigated:

- Discharge voltage
- Electrode gap/surface area
- Electrode material
- Electrolyte conductivity and type
- Circuit capacitance and inductance

It was found that the efficiency of the spark process improved with voltage due to the reduction in time between applying the voltage and the spark forming. The acoustic output also became more consistent at higher voltages. Below 4 kV the discharges were very erratic.

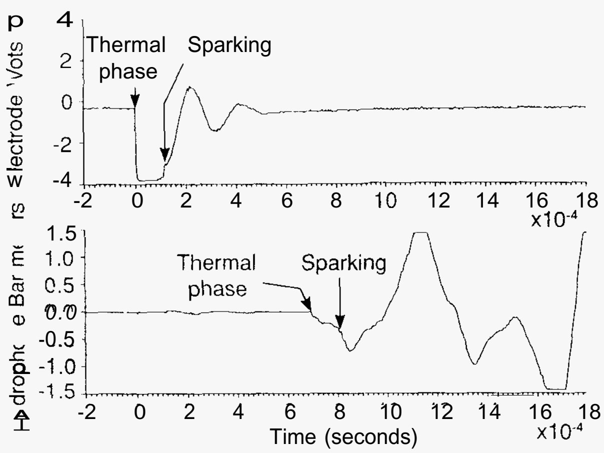
The acoustic output increased with decreasing electrode tip area but the tip material appeared to have no effect. For any particular voltage and electrode area there was found to be an optimum electrode gap and electrolyte conductivity. The type of electrolyte appeared to be insignificant.

From observations of the light output and electrode voltage during discharge the acoustic pulse was found to have potentially two components, ohmic heating and sparking (Figure 1). Ohmic heating starts immediately the voltage is applied but sparking is delayed until the fluid breaks down and a spark can form. Conversion of electrical to acoustic energy was most effective when the duration of heating was minimised. This could be achieved by minimising the tip area and electrolyte conductivity or increasing the voltage. The discharge circuit behaves as a series resonant circuit where the resonant frequency (f (r)) is given by:

$$f(r) = 1 / 2 * \pi * \sqrt{(L * C)} \qquad (1)$$

where L is the inductance of the circuit and C the capacitance.

Over the range of resonant frequencies investigated, 1700 to 10000 Hz, the acoustic frequency was found to be very similar to the resonant frequency of the circuit. The principle source of resistance in the circuit is due to the spark gap between the electrodes. The maximum acoustic output was produced by adjusting the electrode gap to produce a damped electrical discharge.



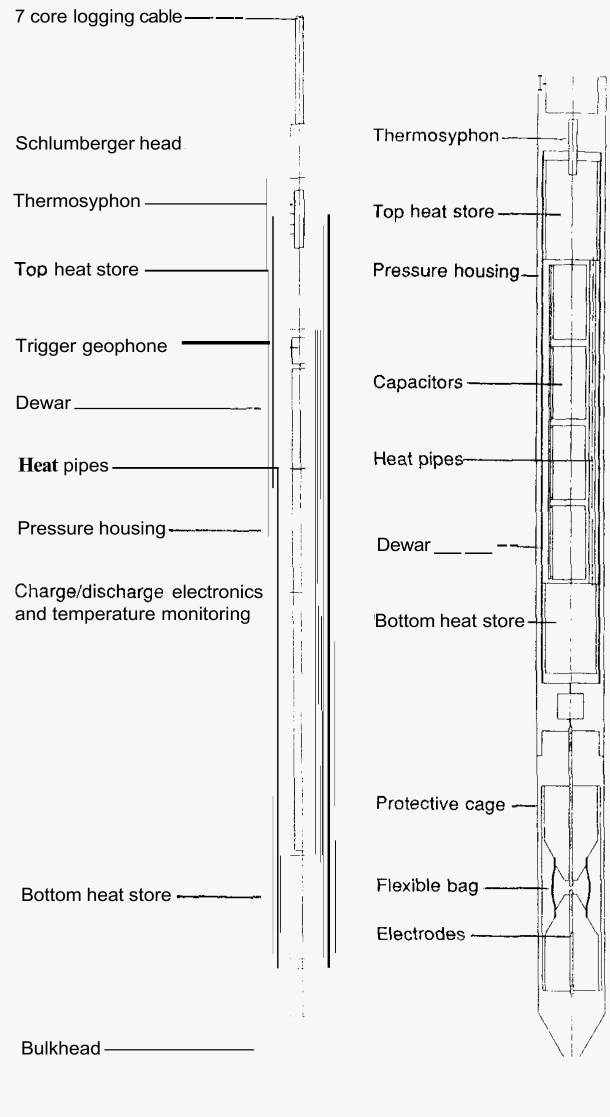
1 Electrode voltage during a 4 kV discharge and hydrophone response recorded at an offset of 1 m.

3 DESIGN ELEMENTS OF THE CSMA HIGH TEMPERATURE SPARKER

A schematic representation of the sparker is given in Figure 2. The tool is divided into two sections 3.5 m and 4 m long for ease of deployment and runs on a industry standard 7 core wireline logging cable. The top section contains a high voltage power supply, trigger geophone and electronics controlling temperature monitoring, charging of the capacitors and shot instant. In the bottom section are capacitors and a high voltage switch which is open during charging and closed to discharge the capacitors across the electrode gap.

In order to restrict heat transfer from the borehole to the electronic components these are contained within a dewar flask in each section. Heat generated within the tool is collected and transferred to thermal stores at each end of the dewar by heat pipes. During operation the temperature inside the dewars builds up slowly due to inefficiencies in the electronic components and heat transfer from the borehole. The thermal stores restrict the rate of rise in temperature by absorbing energy. The capacity and so physical size of the thermal stores is determined by the period of deployment required, the rate of build up of heat energy in the tool and the operating temperature range of the components in the dewar.

The heat generated within the tool per shot is related to the amount of energy discharged. Consequently the choice of discharge parameters for the downhole tool was a balance between the thermal capacity of the tool, the desired acoustic output and the life expectancy of the electrodes. In the final design the electrodes survive around 700 shots which at the charge rates possible on a standard wireline logging cable would take $6\frac{1}{2}$ hours to fire. At the maximum borehole temperature of 200°C the heat stores are designed to keep the internal temperature of each section of the tool within the operating range for 10 hours. This allows time for stoppages during a survey and deployment/retrieval of the tools.



2 Schematic diagram of the CSMA MkII High Temperature Sparker.

Sensors within each section of the tool monitor the temperature at various critical locations. When the maximum permissible internal temperature is reached or the survey is completed the tool is cooled by moving it to a location where the external temperature is lower than the internal temperature. Heat is then transferred from the heat stores by the thermosyphon which acts as a one way valve letting heat out but not in to the tool.

In operation the tool automatically cycles through a sequence of charging and firing. The shot instant is detected either by a current sensor which detects when the spark forms or by a shot instant geophone at the top of the tool. There is a short interval following firing in which nothing happens to allow the shot instant data from the geophone/current sensor to be collected without electrical interference. Operating at 5 kV the shot interval is 35 s.

4 DOWNHOLE TRIALS

4.1 High temperature tube wave survey

In April 1993 the high temperature performance of the sparker was tested in well GPK1 at Soultz. A survey was performed over the openhole section of GPK1 between 3470 m and 2850 m measured depth at 1 m intervals. At each level a single shot was fired and recorded on the trigger geophone at the top end of the tool, a distance of 7 m.

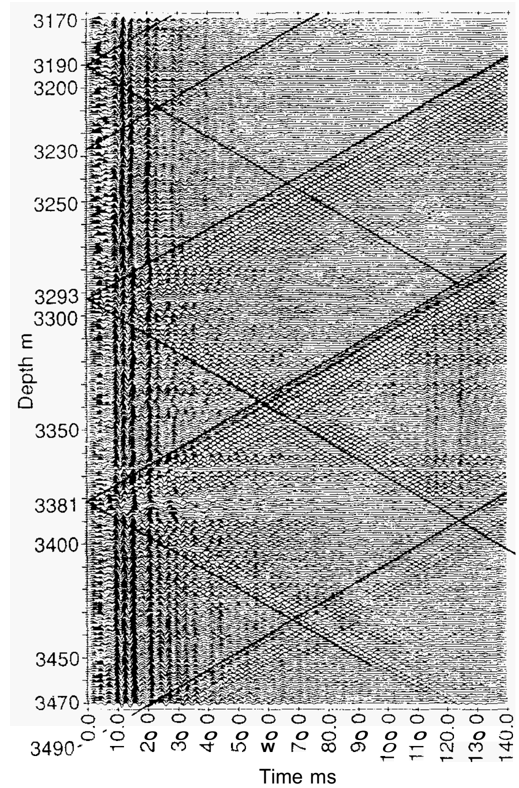
Tool performance

The temperature over the survey interval increased from 150°C at 2850 m to in excess of 160°C at 3470 m. This provided a good opportunity to test the effectiveness of the thermal system in keeping the internal operating temperature of the tool within rdnge.

Over the longest uninterrupted sequence of shots there were 473 discharges and the interior temperature of the electronics section of the tool rose by 31°C. The temperature sensor in the capacitor section failed after 165 shots and an 11°C temperature rise. The discharge voltage was 4.5 kV. From these observations, over the 700 shot design life of the electrodes, a temperature rise of 50°C in the electronics section and 47°C in the capacitor section may be extrapolated.

The temperature rise observed in the capacitor section was too high to have completed a full run of 700 shots. However, this was because shots were fired at less than half of the maximum rate, to allow the tool to be moved between shots. Subsequently the tool has heen fired continuously whilst being pulled up the borehole in a logging type operation. This significantly reduces the time the tool is exposed to external heating from the well.

The effectiveness of the dissipation of heat from the sources of internal heating to the heat stores has also been improved by replacing the eutectic material used previously for the heat stores with copper. It was found that the eutectic material, which has a low thermal conductivity, tended to melt around locations of heat input but may not have beer; absorbing heat efficiently. Although copper has a slightly lower heat capacity than the eutectic material, over the internal operating temperatures of the tool sections, it is far more conductive than the eutectic material and so would more readily absorb heat.

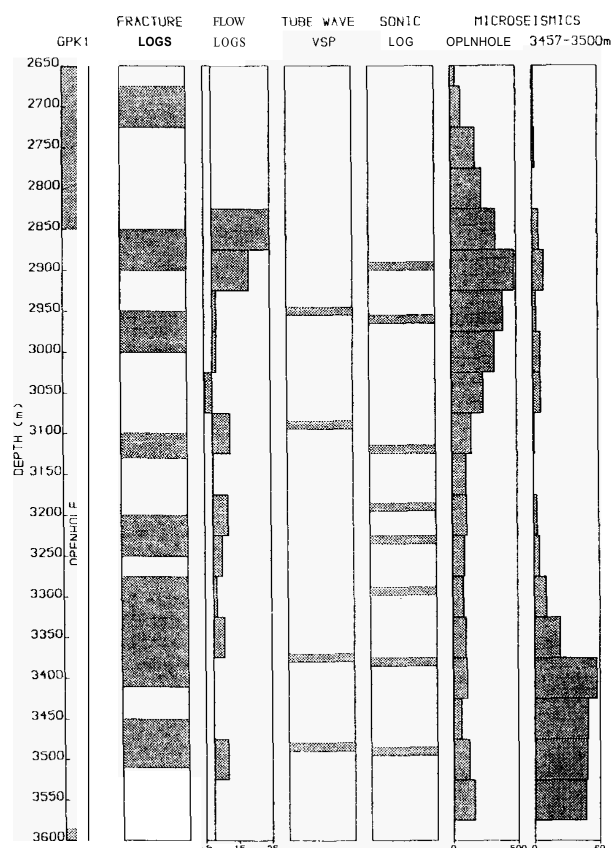


3 Sparker tube wave log in borehole GPKl at Soultz from 3171 m to 3470 m.

Survev results

The configuration of the electrode/geophone separation was such that the survey effectively formed a long spaced sonic log. From the survey data a number of tube waves were readily identifiable (Figure 3). In addition to the sparker survey, fractures in the well have also been identified from surface tube wave VSPs, flow/temperature logs, fracture logs compiled from borehole imaging data and the depth distribution of micro-seismic activity within 100 m of the well during. The flow/temperature and microseismic data were acquired during hydraulic stimulations between 3457 m and 3507 m and over the whole openhole.

A composite of all the log data, including tube wave locations picked from the sparker survey, is given in Figure 4. There is clearly a strong correlation between features identified by the various techniques. The tube wave logs are of particular interest as they resolved individual flow entry points, to within a few metres, prior to the hydraulic stimulation which were subsequently confirmed from the flow logs during stimulation. This observation suggests that the tube wave techniques could be used to identify fractures which are permeable or might be stimulated.



4 Summary of fracture data from borehole GPKl at Soultz including logged fractures from BHTV/FMS, flow exits from flow logs, tube waves from surface VSP/sonic log and microseismic event distribution.

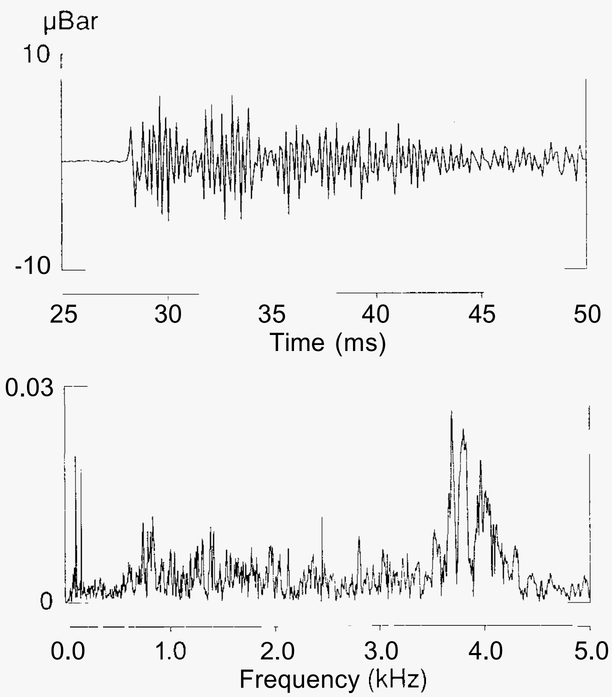
4.2 Cross-hole demonstration

As part of the development programme a downhole test was performed following the completion of most of the planned modifications to the tool. During this test a discharge voltage of 4 kV instead of the maximum of 5 kV was used to minimise the potential damage in the event of unforeseen problems arising.

For the test a survey was performed over the openhole sections of two wells at CSMA, RH11 and RH12, where the borehole separation is 150 m. A hydrophone was located at 2165 m in RH11. The sparker was raised at a rate of 0.02 m/s in RH12 whilst firing at intervals of 25 s giving a source interval of approximately 0.5 m.

On the basis of laboratory trials the electrodes were expected to last in excess of 700 shots. The survey was stopped at 500 shots to assess the electrode wear which, after allowing for the reduced operating voltage, was consistent with the anticipated life expectancy.

A typical hydrophone trace from this survey is shown in Figure 5 together with the frequency spectrum. There is a broad spread of energy from less than 1 kHz to more than 2.5 kHz. Above 3 kHz there is a strong concentration of energy which is characteristic of cross-hole surveys at this site and is not thought to be generated directly by the source. Frequencies significantly higher than 4 kHz would have been lost as the anti-alias filter was set at 4 KHz and the Nyquist frequency was 5 KHz.

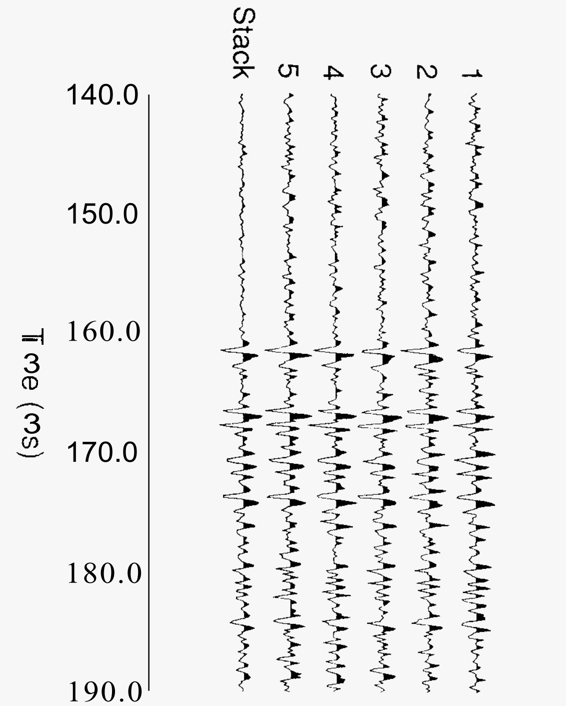


5 Typical cross-hole trace and spectrum for a source at 2166 m in RH12 and receiver at 2165 m in RH11 at CSMA.

4.3 Penetration Test

In order to determine the maximum penetration of the tool tests were performed between the sparker in borehole RH12 and hydrophone in RH11 at CSMA. The hydrophone was located at a constant measured depth of 2160 m and the sparker deployed at increasing offsets by raising it in the borehole.

Five traces recorded at an offset in excess of 800 m are shown in Figure 6 together with a stack of the same traces. The P wave arrival can be clearly seen, even in the unstacked data, and has a frequency of a little less than 1 kHz. These data are particularly encouraging as the source was being operated in casing, which would be expected to attenuate the signal, and at an angle of more than 70° to the wells. From the radiation pattern study, the trace amplitude at this high angle would be expected to be less than 10% of that of a path perpendicular to the boreholes.



6 Five traces and their stack recorded at a constant offset in excess of 800 m in granite at CSMA.

5 CONCLUSIONS

A high temperature downhole sparker seismic source has been developed which is capable of firing 700 shots per deployment at borehole temperatures of up to 200°C over a period of 10 hours. The penetration of the tool in granite has been found to comfortably exceed 850 m without stacking and the borehole radiation pattern is similar to that of a point source in a borehole. The source produces both P and S wave energy at observed frequencies of 1 - 2 kHz when used in a cross-hole configuration.

A number of surveys have been performed which have demonstrated the suitability of the sparker both as a cross-hole seismic source and as a long spaced sonic tool for identifying tube waves. The thermal performance of the tool has been tested successfully at 160°C and it is expected that the 200°C specification of the design will be achievable

ACKNOWLEDGEMENTS

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