High temperature instruments and methods developed for supercritical geothermal reservoir characterisation and exploitation—The HiTI project

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1. Introduction

This paper gives an overview of achievements made within a partnership formed in the so-called HiTI project (High Temperature Instruments for supercritical geothermal reservoir characterisation and exploitation), funded within the Sixth Framework Programme of the European Union, project number 19913.

Supercritical reservoirs are expected to exist below conventional high temperature geothermal fields. The supercritical fluid can in simple terms be described as having the density of water, but flow properties like a gas. This could mean that the permeability for the supercritical phase is very high, either in dense brittle or ductile rock. The potential of supercritical geothermal fluid utilisation has been described in several Iceland Deep Drilling Project publications; see e.g. Fridleifsson and Elders (2005) and references therein. A model of the hydrothermal processes near a brittle–plastic rock transition was described by Fourrier (1999). IDDPP wells were subsequently planned to be cased off at 3500 m depth, where a boiling curve to surface would reach the critical point at a pressure of 22 MPa and temperature above 374 °C for pure water.

Future supercritical geothermal reservoirs will need to be evaluated in situ with instrumentation and methods adapted to the supercritical environment. The HiTI project, when first planned in 2004, was designed to provide at least the minimum...
instrumentation needed to allow the scientific community and geothermal industry to evaluate a supercritical geothermal reservoir. The primary indicators of geothermal power are of course the thermodynamic parameters, and therefore a large emphasis was put on direct downhole measurements of temperature, pressure and flow at as high temperature as possible. This was achieved both with improved wireline measurements and a memory tool on a slickline. A slickline is a strong armoured cable containing one or more conducting insulated wires through which constant power can be provided and communication to surface is achieved. A slickline is a metal wire that can be used to lower a non-communicating device to great well depths and temperatures exceeding the tolerance limits of any commercial wirelines. Both wirelines and slicklines need to tolerate high temperature and corrosive geothermal well environments. The two tools developed and field tested for the thermodynamic evaluation were a wireline temperature sensor operating long-term without heat shielding up to 300 °C and a slickline temperature, pressure and flow instrument in a heat shielding flask tolerating 400 °C for a few hours. In addition to the downhole tools, a fibre optic distributed temperature sensing (DTS) cable was developed and installed along the outside wall of a 300 m anchor casing of a new powerful production well. This latter technique allows for an instantaneous measurement of temperature along the whole length of installation. Temperature changes or anomalies within that section can be monitored at any time, at first during cementing and drilling (Henninges and Brandt, 2007) and then later during flow testing and even production.

The rock properties of the deep reservoir remain of great interest, since the geothermal fluid flow properties are determined by the formation characteristics. For the purpose of identifying rock properties (e.g. fractures, formation change, resistivity and borehole wall rugosity), firstly a televiewer was demonstrated at 300 °C in a well in Iceland along with a spectral natural gamma radiation tool and secondly a resistivity tool of the dual laterolog type was designed for operation at 300 °C on wireline but unfortunately could not be field tested within the project.

Knowledge on the chemical content and the resulting properties of the fluid at both supercritical and subcritical conditions are of high interest regarding both field conceptualization and utilisation for power production. Fluid samples were collected at wellheads from several high temperature Icelandic geothermal fields and two new sodium(Na)/lithium(Li) ratio geothermometric relationships (with determination of the corresponding Li isotope values) were designed in order to determine with more detail the temperature in very high temperature geothermal systems. Tracer testing with organic isomers was also carried out within the Krafla geothermal field in Iceland where the first IDDP well is located, showing very high tracer linear velocities, both from the site’s main re-injection well and the IDDP-1 well itself.

Basalt rock from cored wells from the Krafla field was tested in a Paterson pressure cell which had been modified to allow for (1) fluid injection of various compositions, (2) electrical resistivity measurements at a few mV of AC voltages ranging from 0.1 Hz to 10 MHz and finally and (3) deformation pressure experiments at up to 300 MPa and 900 °C.

The project intermediate results were published on the HiTI website www.hitl-fp6.eu during the active phase and fully disseminated in several reports referenced below. This is however the first publication describing the overall project outcomes. The participants and their roles are listed in Table 1.

The new instruments and methods have now been field tested and applied to extract scientific information at several different high temperature field locations in Iceland. In addition, commercialisation of some of the technologies has already taken place, satisfying the conventional high temperature geothermal industry and science while marginally keeping up to the pace of deep high temperature drilling efforts (the IDDP-1 wellhead became hotter than anticipated within the HiTI project).

2. Thermodynamic parameters

For the identification of thermodynamic parameters, crucial to geothermal power production, the following four instruments and methods were completed and applied:

1. New geothermometric relationships using Na/Li cation ratio and the corresponding lithium isotopes values were determined by BRGM using liquid samples collected in 2007, 2008 and 2009 in Icelandic high temperature fields.

2. Distributed temperature sensing (DTS) fibre optic cable was installed by GFZ-Potsdam in 2009 in well HE-53 in the Hellisheiði geothermal field, Iceland.

3. Temperature sensor operating to 300 °C on a wireline, designed by BRGM and field tested together with ISOR in the Krafla geothermal field, Iceland.

4. Temperature, pressure, fluid flow and casing collar location tool was designed and built by Calidus Engineering and field tested together with ISOR in the Krafla geothermal field in July 2010.

Each of these thermodynamic parameters is discussed in separate sub-sections below.

2.1. New Na/Li geothermometric relationships

One of the major applications of water geochemistry in the exploration of the potential geothermal reservoirs involves estimation of their deep temperature using analyses of some chemical or isotopic species performed on fluids collected from thermal springs or geothermal waters. Most of the classical chemical geothermometers such as silica, Na/K, Na/K/Ca, K/Mg or Na/K/Ca/Mg (Nicholson, 1993) are based on empirical or semi-empirical laws derived from known or unknown chemical equilibrium reactions between water and minerals occurring in the geothermal reservoirs. Unfortunately, the estimations of temperatures given for the deep geothermal reservoirs using these classical tools are not always concordant due to different processes which can occur during the ascent of the deep water and can modify its chemical composition (mineral precipitation or dissolution due to the fluid cooling, fluid mixing with shallow aquifers, etc.). Given these discordances, auxiliary geothermometers such as the three Na/Li ratio relationships based on statistical analyses were determined (Fouillac and Michard, 1981; Kharaka and Mariner, 1989). Even if the chemical processes which control the Na/Li ratio are still poorly known, these relationships give more reliable deep temperature estimates than the classical geothermometers in numerous cases because of the low lithium reactivity during the ascent of the deep fluid (Fouillac and Michard, 1981). However, their use must be selective taking into account the fluid salinity and/or the nature of the rocks which constitute the studied reservoir (granitic, basaltic, andesitic or sedimentary rocks, for example).

The geothermometric analysis by BRGM was initiated with a bibliographic study on the application of the sodium–lithium ratio and the existing Li isotope values to identify reservoir temperatures and characteristics previously reported (Sanjuan and Millot, 2009). Water sampling from producing high temperature wells was conducted in October 2007, June 2008 and June 2009 (Sanjuan et al., 2010 and Sanjuan, 2010). These water samples were chemically and isotopically analysed in the BRGM laboratories. A new statistical Na/Li relationship was first identified for dilute non marine geothermal waters from Iceland with temperatures ranging from 200 to 325 °C (Fig. 1; Sanjuan et al., 2010).
Another statistical Na/Li relationship was also obtained between 0 and 365 °C for seawater–basalt interaction derived hydrothermal fluids from rifts that have emerged above sea level such as those of Iceland (Reykjanes, Svartsengi and Seltjarnarnes geothermal fields) and of Djibouti (Asal and Obock geothermal areas), or from numerous oceanic ridges and rises worldwide (Fig. 1; see references in Sanjuan, 2010). A new publication describing the two identified relationships is pending (Sanjuan et al., 2013).

These relationships were in our studies determined to have an accuracy of ±25 °C and have the linear generic appearance:

\[ \log \frac{Na}{Li} = \frac{a}{T} - b \]

where the constants \(a\) and \(b\) are different for each type of water environment, listed in Table 2. Na and Li represent the concentrations of each species expressed in mol/l.

As observed in Fig. 1 and in Table 2, the two new Na/Li relationships are very different from those known in the literature to date (Fouillac and Michard, 1981; Kharaka and Mariner, 1989) and confirm that the Na/Li ratios not only depend on the temperature but also on other parameters such as the fluid salinity and origin, or the nature of the geothermal reservoir rocks in contact with the deep hot fluids. We can conclude that it is essential to well define the environment in which the Na/Li geothermometer is applied before its use. Some case studies found in the literature and thermodynamic considerations as shown in Sanjuan et al. (2010) or Sanjuan (2010) suggest that the Na/Li ratio is probably controlled by different full equilibrium reactions at high temperatures involving feldspars, quartz and clay alteration products, partially constituted of illitic and mica minerals where lithium would be incorporated.

The corresponding Li isotope values (\(\delta^7Li, \text{in ‰, Fig. 2}\)) indicate that the values associated with the seawater derived hydrothermal fluids mostly range from +2 to +11 ‰ and that the values associated with the Icelandic dilute non marine geothermal waters can vary between +3 and +8 ‰ (Millot et al., 2013). These data are very different from those obtained by Millot et al. (2012), for New Zealand high temperature geothermal fluids which indicated low and extremely homogeneous values ranging from −0.52 to +1.42 ‰. For the first type of waters, their measured Li isotope values are clearly much lower than that of the seawater (\(\delta^7Li \approx +31 \text{ ‰}\)) and their higher Li/Cl ratios indicate that these waters have intensively interacted with basalts, even at 114 °C (Fig. 2). However, their significant Li isotopic variations at high temperatures (despite a low isotopic

**Table 1**

Participants in the HiTI project.

<table>
<thead>
<tr>
<th>Participant name</th>
<th>Short name</th>
<th>Country</th>
<th>Role in project</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iceland GeoSurvey</td>
<td>ISOR</td>
<td>Iceland</td>
<td>Coordination/field demonstration</td>
</tr>
<tr>
<td>Géosciences Montpellier, UM2, CNRS</td>
<td>CNRS</td>
<td>France</td>
<td>Rock physics – log data modelling</td>
</tr>
<tr>
<td>Bureau de Recherches Géologiques et Minières</td>
<td>BRGM</td>
<td>France</td>
<td>Water chemistry, downhole tool development, tracing tests</td>
</tr>
<tr>
<td>Calidus Engineering Ltd.</td>
<td>CalEng</td>
<td>United Kingdom</td>
<td>Downhole tool development</td>
</tr>
<tr>
<td>Advanced Logic Technology</td>
<td>ALT</td>
<td>Luxembourg</td>
<td>Downhole tool development</td>
</tr>
<tr>
<td>Oxford Applied Technology Ltd.</td>
<td>Oxatec</td>
<td>United Kingdom</td>
<td>High temperature electronics</td>
</tr>
<tr>
<td>German Research Centre for Geoscience</td>
<td>GFZ</td>
<td>Germany</td>
<td>Distributed temperature sensing</td>
</tr>
<tr>
<td>Centre for Renewably Energy Sources</td>
<td>CRES</td>
<td>Greece</td>
<td>Dissemination</td>
</tr>
</tbody>
</table>

Fig. 1. The two new geothermometric Na/Li relationships revealed by BRGM within the project, using sampled fluids from several geothermal fields in Iceland, and the three existing Na/Li relationships in the literature: (a) Fouillac and Michard, 1981, for fluids with Cl > 0.3 M; (b) Kharaka and Mariner, 1989, for oil and sedimentary basin fluids; and (c) Fouillac and Michard, 1981, for fluids with Cl < 0.3 M.

Fig. 2. Li isotopic values measured in the literature (Sanjuan and Millot, 2009) and during this study as a function of the Li/Na ratios.
fractionation between the fluid and the rock (Millot et al., 2010) suggest that the chemical compositions or the alteration grades of the basalts in contact with these fluids are different (Sanjuan and Millot, 2009). For the second type of waters (Icelandic dilute non marine geothermal waters), their Li isotopic values are less scattered but most of their Li/Na ratios are higher and indicate much more variations than for the first type of waters. The influence of the heterogenous chemical compositions or the different alteration grades of the volcanic rocks in contact with these waters seems to be more significant than that of the temperature on the Li isotopic values but not on the Li/Na ratios.

2.2. Distributed temperature sensing

Fibre optic distributed temperature sensing (DTS) measurements based on Raman backscattering allows for a quasi-continuous temperature measurement over the whole length of a fibre optic cable. Using a permanent installation of the cable behind casing, long term temperature monitoring during cementation, testing, production or workover activities can be performed without well intervention. To acquire a temperature profile, a laser pulse is coupled into the fibre and backscattered photons of the two Stokes intensities can be calibrated to temperature. The ratio of the two Stokes intensities can be a requirement to measure temperature downhole in real time using a wireline system, e.g. to actively excite or diminish thermal inflow and follow the response interactively.

Prior to the installation in Iceland different commercially available optical fibres, suitable for the deployment under the harsh conditions of a conventional geothermal well, have been tested with a hermetic carbon layer has been shown to possess the most reliable temperature (Reinsch and Henninges, 2010). Among these were fibres with polyimide as well as metal coatings. Despite its limited temperature range of up to 300 °C, a polyimide-coated fibre with a hermetic carbon layer has been shown to possess the most favourable properties at conditions expected during the production of hot fluid in a conventional geothermal well. After selecting the most proper fibre, a fibre optic wellbore cable for DTS measurements was developed and manufactured as well as temperature tested up to 280 °C in collaboration with nkt cables GmbH, Cologne (Geckies et al., 2009). The fibre optic cable is comprised of a double-walled steel tube with an intermediate layer of bronze wire. The outer jacket is formed by a PFA layer with an outer diameter of 5 mm (Reinsch et al., 2013).

The fibre optic cable was installed in May 2009 in well HE-53 in the Hellisheiði field along the outside wall of the 300 m deep anchor casing and attached to the casing centralizers. The cable formed a loop, with the lowest point at 270 m depth and the two ends extending on either side of the casing back to the surface. Temperature was measured during cementing in May 2009 and then again during flow testing in July and August as well as after a 9 month shut-in period in August 2010. Maximum temperatures up to 230 °C were measured after two weeks of flow testing in August 2009. A detailed description of the installation as well as measurement data and data accuracy can be found in Reinsch et al., 2013. Video 3 shows a short section of the installation procedure.

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.geothermics.2013.07.008.

2.3. Temperature sensor on wireline to 300 °C

Commercial wirelines cannot operate beyond 300 °C and experimental wirelines rated at higher temperature are currently not available. One of the most notable experimental wireline is the ENEI/CISE HostEn cable which was assembled almost twenty years ago, rated to 400 °C and performed well at 300 °C (Arisi et al., 1995). Due to this wireline temperature limitation, electronic memory tools are deployed on a slickline to obtain measurements at higher temperatures (up to 370 °C using current high-end commercial tools). The results of a memory tool measurement only become available after the tool is extracted from the well and no ‘live’ measurements are available. However, in certain circumstances, there can be a requirement to measure temperature downhole in real time using a wireline system, e.g. to actively excite or diminish thermal inflow and follow the response interactively.

The project’s wireline temperature tool was designed by BRGM, based on a previous design by R. Gable, and demonstrated successfully in June 2010 in the Krafá geothermal field. The tool is analogue (no electronics inside) and uses the well-established technique of recording platinum resistance changes that are calibrated to temperature (Lebert, 2010). The tool was demonstrated in well KS-01 in Sandabotnaskarð to 316 °C, which is the temperature limit of the wireline cable, see Fig. 3. The tool was however designed to tolerate 400 °C and field testing at that temperature can be performed once suitable wireline cables become available. The Rochester 4-conductor wireline used within the HTI project (labelled as type 4-H-314M) for tool testing in hot geothermal wells performed exceptionally well and even though the armour was blackened after sulphur scaling, the insulation looked like new when inspected after the different runs.

Table 2
The two new geothermometric Na/Li relationships developed by BRGM within the project, using sampled fluids from several geothermal fields in Iceland, to be used with Eq. (1), and the three existing Na/Li relationships in the literature (r² is the regression coefficient).

<table>
<thead>
<tr>
<th>Type of water</th>
<th>Location</th>
<th>Temperature range</th>
<th>a</th>
<th>b</th>
<th>r²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seawater-basalt</td>
<td>Reykjanes, Svartsengi and Seltjarnarnes geothermal areas (this study), Djibouti geothermal areas and worldwide oceanic ridges</td>
<td>0–365 °C</td>
<td>920</td>
<td>1.105</td>
<td>0.994</td>
</tr>
<tr>
<td>Icelandic dilute non marine geothermal waters</td>
<td>Krafla, Nesjavellir, Námafjall and Hveragerði geothermal areas (this study)</td>
<td>200–325 °C</td>
<td>2002</td>
<td>–1.322</td>
<td>0.967</td>
</tr>
<tr>
<td>Dilute geothermal waters (Cl &lt; 0.3 mol/l)</td>
<td>Worldwide volcanic and granitic geothermal areas (Fouillac and Michard, 1981)</td>
<td>0–340 °C</td>
<td>1000</td>
<td>–0.38</td>
<td>0.965</td>
</tr>
<tr>
<td>Saline geothermal waters (Cl ≥ 0.3 mol/l)</td>
<td>(Fouillac and Michard, 1981)</td>
<td>0–340 °C</td>
<td>1195</td>
<td>0.13</td>
<td>0.982</td>
</tr>
<tr>
<td>Saline waters</td>
<td>Worldwide oil, sedimentary basins and geothermal areas (Kharaka and Mariner, 1989)</td>
<td>0–350 °C</td>
<td>1590</td>
<td>–1.299</td>
<td>0.910</td>
</tr>
</tbody>
</table>

1 As a ‘historic note’, it was pointed out to the authors by Paul Bixley, Contact Energy Ltd., that a Wheatstone bridge circuit was used in the first wireline logging setup in New Zealand back in 1968. The BRGM sensor does not use a Wheatstone bridge, which is a resistivity balancing technique, but relies on the current commercial availability of higher impedance voltage gauges which allows direct and accurate evaluation of the potential drop over a resistive object with a known (measured) electric current running through it.
2.4. Temperature, pressure, fluid flow and casing collar sensing on slickline to 400 °C

Supercritical water temperatures start at 374 °C, and therefore it was determined that at least one instrument to be provided by the project would need to be able to accurately measure thermodynamic parameters within a supercritical reservoir. That tool is the so-called MultiSensor, designed and built by Calidus Engineering. The tool is a memory tool, i.e. lowered into a well on a non-communicating slickline and records temperature, pressure, fluid flow and casing collar location into the tool’s on-board memory that can be accessed once the tool reaches surface again. A demonstration was performed in July 2010 in two wells, KS-01 and IDDP-1, the latter well at that time with 360 °C at the wellhead. The temperature recordings from well KS-01 compared very well with both BRGM’s wirline temperature tool and also calibrated temperature instruments owned by ISOR. Within the IDDP-1 well, the tool was shown to be able to tolerate the ‘shock-treatment’ of the abrupt temperature rise when the wellhead valve is opened to the exposed tool, see Fig. 4. The spinner had some difficulties in the superheated steam environment, but both pressure readings and casing collar locations were recorded with high accuracy.

The existence of this tool has recently become of more importance, since the IDDP-1 well has continued to heat up, with wellhead temperature now reaching 450 °C. The setup during tool testing at IDDP-1 is shown in Fig. 5. Videos 2 and 3 show the approach to the well and the instrument inside the tool tube during testing.

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.geothermics.2013.07.008.

3. Rock physical parameters and borehole characteristics

In any geothermal exploration, knowledge on the reservoir’s formation properties and rock physical parameters are essential. As an example, the brittle to ductile transition in deep rock formations may strongly influence the rock’s geothermal fluid transport properties. Core fragments were obtained from well IDDP-1 in Krafja, but only at roughly 2100 m depth (Friðleifsson, 2010). Despite the lack of deep cores, laboratory testing of basaltic rock was performed within the HiTI project on available cores from shallower depth within the Krafja field, in order to obtain knowledge on the interaction of supercritical geothermal fluids with basaltic formations. Also within the HiTI project, a televiwer and a spectral natural gamma radiation instrument, both operating at 300 °C have been developed. The images and radiation spectrum from that combined tool can be used in a complete comparison study with extracted future deep cores.

3.1. Basalt core studies

An hybrid experimental cell for laboratory measurements of basalt cores subjected to high temperature and pressure while measuring resistivity over the cores was performed in an upgraded...
The new cells allows resistivity measurements to be conducted at confining pressure up to 200 MPa, pore pressure up to 50 MPa and temperature up to 500 °C (Violay et al., 2011). In addition, deformation studies of both glassy and non-glassy basalt were conducted under oceanic crust conditions, revealing a possible brittle to ductile transition in Icelandic glassy basalt at around 100–200 °C but at 550 ± 100 °C for non-glassy basalt (Violay et al., 2010, 2012). These studies improve our understanding of the thermal properties of unconventionally deep geothermal systems, currently unexplored directly and only inferred with e.g. seismic studies, see e.g. Ágústsson and Flóvenz (2005). An interesting comparison of the basalt studies mentioned above can be made with previous laboratory experiments on granite (Takahashi et al., 2003), where a drastic enhancement of permeability was observed when temperature in a pressurised cell exceeded the critical point of water. A similar study with basalt cores should be conducted.

3.2. Televiewer and natural gamma radiation borehole instruments

The first demonstration of the televiewer prototype combined with a natural gamma spectrometer was carried out in November 2008 in well K-18 at Krafla. That well is located on top of a known supercritical region that was ‘unintentionally’ drilled into from well K-39 a month earlier (Árnadóttir et al., 2009). Casing thickness measurements were also carried out in two wells using the televiewer, applying the new casing thickness evaluation features made available within the HiTI project (Massiot et al., 2009, 2010). A casing thickness profile from well B-14 in Bjarnarflag was recorded with the high temperature televiewer prototype from ALT in November 2008, shown in Fig. 6. During the final demonstration in December 2009, the high temperature televiewer successfully reached 300 °C in well B-14 in Bjarnarflag, see Fig. 7. On tool recovery from the well after a total operation time of around 7 h, thereof for roughly 3 h in a 250–300 °C environment, the electronics were at 43 °C. This internal electronics temperature gradient is near linear and indicates that the 125 °C tolerant electronics could last up to 30 h at these high temperatures.

3.3. Dual laterolog resistivity borehole instrument

A downhole resistivity instrument (a dual laterolog rated to 300 °C) was developed by Calidus Engineering but the latest prototype could not be prepared for field testing within the project, primarily due to budget constraints. The tool remains with Calidus Engineering and can be made available for future deep and hot wells.

4. Reservoir and fluid circulation characteristics (tracing tests)

For utilisation of a supercritical geothermal system, the subsurface fluid flow properties at depth need to be revealed. Tracer testing remains the most powerful method to determine fluid flow paths, using foreign elements mixed with re-injection waters and monitoring their return from production wells and other flowing wells within the geothermal area under study. By combining geological and geophysical studies, such as transient electromagnetic, magnetotelluric and seismic methods with the reservoir properties revealed by tracer testing, an overall conceptual model is derived.

Selection of tracer relies on a combination of properties: a good tracer must be inexpensive, absent from the original fluid, conservative (chemically non-reactant, nor adsorptive), easily soluble,
detectable at very low concentration and environmentally safe. Additionally in geothermal fields, tracers have to be thermally stable and their behaviour with respect to the phase change must be known: preferably they have to concentrate either in the liquid or in the vapour phase (see e.g. Rose et al., 2009). The supercritical conditions strengthen the last selection criteria. The tracers tested at Krafla within the HiTI project are naphthalene disulfonate (NDS) isomers, selected since they are tolerant at high temperature (up to 340–350 °C; Rose et al., 2001 and a geothermal application in Sanjuan et al., 2006), concentrate in the liquid phase, non-toxic, can be discriminated and accurately detected (by HPLC) until 0.25 g/l.

As the Krafla geothermal field has been studied and harnessed for about 40 years, the tracing operation could rely on the relatively good knowledge of its structure that includes schematically from the top to the bottom a liquid dominated system, a vapour one and possibly, locally supercritical conditions.

The tracers were injected into both the main injection well at Krafla (K-26) and the IDDP-1 well during drilling. The results showed very high linear fluid velocities: 14 m/h from the K-26 well, into the upper part of the field and, at least, 320 m/h from the IDDP-1 well, presumably near a cooling magma body. From those velocities, very high flow rates could be inferred in the geothermal system (see Fig. 8). This result was so unexpected that at the first tracing test in K-26, the tracing material could not be recovered as the tracer was dispersed before the beginning of its sampling (Gadalia et al., 2010).

Moreover:
- there were significant anomalies that could be interpreted as thermal impacts: they were correlated to the thermal instability of the isomers and to the location of very high temperature at the bottom holes,
- the dispersion of the tracers was extreme and the tracers reached a majority of productive wells, allowing to infer that all the fault systems were involved.

All those results are consistent with abnormally high temperature conditions and particularly mobile fluid, both of the supercritical characteristics. Work is now in progress to evaluate further the implication of the findings and to repeat the testing with additional tracer types.

5. Future instrumentation

The instrumentation and methodological improvements made within the HiTI project only open the door to the supercritical regime, and will do not provide a full solution for the geothermal scientists and industry. Several new downhole tools have been suggested, applicable also for existing conventional high temperature fields and future enhanced geothermal systems. An international partnership on improving geothermal techniques was recently formed between several countries and one of the working groups formed recently published a White Paper listing the current consensus on the immediate improvements required by both the

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Fig. 8. Monitoring of the 1,5 – NDS content from selected wells.

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International Partnership of Geothermal Technology (IPGT), consisting of the United States of America, Iceland, Australia, Switzerland and New Zealand.
5.1. High temperature electronics

Most commercially available high temperature electronics are limited to 225 °C operation with some excursions to 300 °C. These electronics are based on Silicon-on-Insulator technology (SOI). SOI was initially developed for radiation hardening silicon devices and more recently, for low power applications. This works by limiting the actual devices to a thin layer of silicon separated from the bulk by a buried oxide layer thus isolating the active devices from major leakage pathways. SOI has also been exploited for high temperature devices; again the advantage afforded by confining the active electron part of the device to only a thin isolated layer cuts off the major leakage paths that would otherwise limit the temperature at which devices could operate. High temperature SOI devices are now widely available with tens of thousands of certified operating lifetimes at high temperatures (225 °C).

However, silicon, even SOI, has an intrinsic upper operating temperature derived from the thermal activation of carriers within the material. To overcome this, wider band gap (WBG) materials such as silicon carbide (SiC) and diamond must be utilised. However, the technology for producing devices from these materials is much less mature than that for silicon or SOI.

The development of SiC has been driven primarily by solid state lighting applications where SiC is used as a substrate material for growth of hetero-epitaxial GaN which can be fabricated into a blue light emitting diode. A secondary driver for SiC development has been for power electronic devices where SiC offers a distinct advantage over silicon by being able to withstand higher voltages and operate at higher current loadings enabling smaller more efficient power electronics to be developed.

A few groups have demonstrated limited integrated devices fabricated from SiC. Such devices tend to be simple operational amplifiers or very simple logic circuits. The main driver has been for space applications particularly coming from NASA requirements for electronics for a possible Venus Lander mission. However, in that instance the lifetimes required are measured in hours, 10 h at most and thus are unlikely to furnish technologies suitable for the current geothermal requirements. There are exceptions to this and Raytheon Systems Limited are developing relatively complex SiC based circuitry that should operate to 500 °C; however, such developments are at an early stage and it may be several years before the devices needed by complex instruments capable of 500 °C operation are realised.

Even if devices capable of 500 °C operation were currently commercially available, the question of how to package these devices remains, on the whole, unanswered. The primary options would seem to be with hybrid thick film ceramic technology but this is as yet unproven for 500 °C operation.

5.2. Sensors

Sensors, including transducers, have now been developed in many fields of science and industry to high temperature tolerances. The future challenge will be to fit these new sensors into a functional downhole system architecture. Currently, advanced acoustic downhole instruments are available, tolerating up to 260 °C (not mentioning the 300 °C televiewer discussed above), which is sufficient for the oil and gas industry and many geothermal applications. Pressure and temperature can now be measured in unshielded (barefoot) tools up to 300 °C and likely that a target of 500 °C or even 600 °C could be reached in the near future on heat shielded electronics tools. Mechanical sensors, such as spinners and calliper arms, suffer serious problems at higher temperatures and the short-term approach will most likely be on increased application of acoustic transducers and even optical devices.

5.3. Housing, sealing and wireline

The downhole tools need to be housed with corrosive resistant metals, most often steel or titanium alloys or nickel-chromium based superalloys, chosen according to the estimated reservoir characteristics. The thermoplastic elements which are used in sensor windows or electrode insulation are often of the PEEK type (polyether ketone). Seals are frequently fluorooelastomers or soft metals, such as silver or gold. High temperature oil and grease is used where required, e.g. as transducer coupling material, in cableheads and pressure capillary tubes. Future tool designs will rely on the available material and further material improvements when they become available.

Memory tools (tools that store data in memory downhole) and other sensing elements can be lowered into wells on strong and corrosive resistant slicklines to any of the reservoirs considered here. However, following upon the Italian HostEn cable development initiative mentioned in section 2.3 above, wireline cables need to be upgraded to the supercritical conditions, possibly also implementing fibre optic cables. The fibre optic cables can be used as sensing elements for temperature and pressure along its length and also for fast tool communication.

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