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# Evaluating Casing Deformations in Geothermal Wells Using Multi-Finger Caliper Data Analysis

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## ABSTRACT

Review of the literature suggests that different modes of casing deformations and failures occur in many geothermal operations. In some geothermal fields, such deformations and failures affect a relatively large percentage of the active wells in the asset. In geothermal wells, casing integrity and load capacity can be degraded by both corrosive and erosive wall loss and by mechanical damage modes, such as Trapped Annular Pressure (TAP) collapse, formation movement induced shears and buckles and parted connections. While conventional gyroscopic surveys can be used to reveal global well path changes, they do not provide sufficient resolution to measure highly localized wellbore trajectory or deformation changes, such as localized shear deformations caused by formation movement. Furthermore, while Multi-finger Caliper (MFC) logging tools can be used to identify local changes in casing ovality, the raw MFC data does not provide an indication of the three-dimensional (3D) shape and accessibility. Therefore, casing shears or buckles are often misdiagnosed as 'collapsed' intervals using conventional well log data and analysis methods, leading to misinterpretations regarding the underlying mechanism and potential mitigation actions, which may include changes to well design, construction or operating practices. If not properly diagnosed and monitored, such deformations can progress, potentially resulting in the eventual loss of access to lower regions of the well, reduced functionality (e.g. reduced flow capacity), or loss of barrier integrity and early forced decommissioning of the well, impacting the productivity and economics of the asset. To accurately identify and measure casing deformations due to formation-induced shear or thermal-mechanical induced buckling, and to be able to differentiate such deformation modes from other modes (e.g. external pressure-induced collapse), suitable MFC log data interpreted using a three-dimensional calculation approach is required.

Raw data from MFC logging tools, in particular casing radii values, are routinely used in geothermal wells to assess casing wall loss due to corrosion or erosion, apparent casing breaches due to parted connections, and to investigate potential flow assurance issues (e.g restrictions caused by scale buildup). By combining two-dimensional (2D) radii measurements with the physical tool geometry using a lab-validated transformation algorithm, a 3D profile of the well can be calculated, allowing for accurate identification and quantitative analysis of deformations; in particular, those induced by formation movements at faults or weak bedding planes. As the geothermal sector moves to more challenging and costly wells (e.g. wells completed for hot dry rock, supercritical and Enhanced Geothermal System (EGS) applications), assuring high well reliability and availability is critical to their long-term safe operation, fluid containment and the economics of the asset.

This paper describes a summary of the common deformation modes affecting geothermal wells, including deformation statistics from literature; MFC logging technologies and limitations in geothermal wells and applications; the MFC 3D data analysis approach; and presents a case study to illustrate how this workflow can be used to diagnose and quantify deformations in geothermal wells. Supplemental analyses, such as the use of processed MFC log data coupled with wellbore-geomechanical structural analyses methods, potential mitigation options to reduce the magnitude or likelihood of casing deformations and associated consequences, and technology gaps and recommendations are also discussed.

## 1. INTRODUCTION

Geothermal wells are commonly drilled into challenging geologic and fluid conditions, including high temperature, highly corrosive, highly fractured and faulted, and tectonically active environments. Most are subjected to large temperature variations over their lifecycle, from well construction, through start-up, operation, interventions and decommissioning. In many applications, the production and injection of geothermal fluids result in wellbore and formation thermal-mechanical induced stresses from changes in pressure and temperature within the wellbore and reservoirs. Depending on the degree and timing of confinement, casing and liner strings subjected to these large temperature variations can experience stresses and deformations that exceed the elastic limit of the tubular materials [Xie 2020].

Changes in pore pressure and temperature within the formation, occasionally in zones above the producing interval, can result in significant formation compaction, lateral movement, surface subsidence, as well as, formation creep, activation of faults or slip events at weak lithological planes/interfaces and seismic events. For example, subsidence and well deformations have been noted in both the Wairakei field in New Zealand [Bixley and Hattersley (1982); Allis (1990); Bloomer and Currie (2001); Koros et al. (2016)] and The Geyers field in California [Allan and Philippacopoulos (1998); Rutledge et al. (2000)]. Such formation movements and thermal loading induced by operations can result in deformations, such as casing shears and buckles, that impede well access, restrict production, and potentially lead to loss of the well. Similar damage mechanisms have been observed in the oil and gas industry; for example, in thermal oil recovery projects and fields prone to depletion subsidence (e.g. chalk reservoirs of the Ekofisk and Valhall fields, sand producing formations in Cold Heavy Oil production) and permafrost thaw-induced subsidence (e.g. Alaska's North Slope) [Schwall et al. (1996); Wagg et al. (1999); Xie and Matthews (2011)]. While the pipe body can withstand considerable local deformation, tubular connections can readily lose their sealabiltiy function, disengage (e.g. jump-in or jump-out) or part when subjected to relatively small amounts of local axial or lateral movement [Xie and Tao (2010); Tao and Xie (2013); Xie et al. (2017)]. As most geothermal wells produce and inject directly through the intermediate casing, which is one of the primary elements of the well's barrier envelope (e.g., as opposed to flowing within production or injection completion tubulars), it is of critical importance that the hydraulic and structural integrity of the casing be maintained. To ensure well barrier integrity over the life of the well, it is critical to understand the severity (i.e. location and magnitude) and rate of progression of wellbore deformations in order to assess well integrity risks and to safely operate the well over its productive service life. Many geothermal tubulars are also subjected to significant erosion and corrosion from produced fluids and solids which can result in wall loss, stress corrosion cracking and significantly degrade the integrity of the casing. When combined with cyclic thermal stresses and localized plastic strains due to buckling or formation movement, such wall loss can rapidly compromise the structural and hydraulic isolation functions of the intermediate casing, in particular in regions near connections.

A number of bottom hole assembly (BHA) logging tools and analysis methods, including gauge rings, stiff strings, impression blocks, 2D MFC log analysis, ultrasonic logs, and cameras, are commonly used to identify the location and magnitude of casing deformations. While these methods can be used to identify the presence of a casing restriction, and potentially provide an indication of the minimum diameter, none can reliably quantify a trajectory shift caused by deformations such as shears and buckles. For example, conventional MFC log analysis yields only stacked 2D cross sections of casing diameter, and while impression blocks, downhole cameras, gauge rings and stiff strings provide indications of obstructions and maximum diameters that may pass through a local deformation, they are unable to represent the 3D local trajectory and deformed shape of the well. As a result, in many cases, the use of such conventional inspection methods leads to the misdiagnosis of shear, sinusoidal and helical buckled deformations as intervals of collapsed casing, resulting in inappropriate and often ineffective mitigation and repair actions, such as costly wedge or milling runs, casing patch and tieback string repairs, or modifications to casing design and cement programs (e.g. in an effort to address perceived external pressure-induced collapse). To identify effective preventative well design/construction options and mitigation operations, the true deformed shape and associated loading mechanism must be properly determined and characterized.

While the conventional analysis of MFC log data yields only a 2D cross-sectional view of the wellbore, data from a suitably configured MFC logging tool and knowledge of the specific tool's dimensions and geometry can be combined with the radial caliper finger measurements to generate the 3D shape of the well. Examination of the 3D shape provides insights into the mode and magnitude of the deformation, potential access limitations, loss of hydraulic isolation and indications of wellbore structural integrity. The analysis of repeated MFC logs over time can be used to assess the rate of deformation over time, which provides critical information on the projected service life of the well relative to the design life, and inputs into well integrity and asset risk assessments. Such 3D wellbore information can be used in conjunction with additional data and advanced analyses tools, such as the use of geomechanical data in coupled wellbore-formation structural models and non-linear finite element analysis (FEA) methods [Xie et al. 2016], to: (i) provide insights into the underlying mechanisms responsible for the deformation, the projected remaining service life of the well and effective mitigation options; and (ii) examine formation properties, and to validate Mechanical Earth Models (MEMs).

This paper describes a number of the tubular deformation modes common to geothermal wells, with examples and statistics on the frequency of deformations observed in some applications identified in the literature. Descriptions of the conventional 2D MFC log analysis method, and how the 3D MFC analysis approach differs is also provided, as are the MFC logging tool configuration and running best practices, and the required data. Several of the challenges in running MFC logs in geothermal applications are also noted. A deformation case study in a fracture-stimulated, hard-rock formation application is presented. Typical deformation modes and some of the associated mitigation strategies that can be utilized for each mode are described. The paper notes how such 3D deformation data can be used to project well life and better understand the underlying deformation mechanisms and associated risks using coupled wellbore-formation FEA methods, and concludes with a few comments on apparent MFC technology gaps in geothermal scenarios and considerations for additional development and advancement of the well integrity analysis tool.

## 2. TUBULAR DEFORMATION MODES

### 2.1 Common Tubular Deformation Modes

Tubular deformations are distortions of the tubular cross section and/or local 3D trajectory (e.g. local curvature) which: (i) impair or limit well functionality or performance (e.g. production or injection rates, operating pressure, temperature); (ii) limit or prevent access and interventions (e.g. limit the diameter, length or stiffness of completion or intervention of BHAs or completion equipment); and/or (iii) compromise the structural/hydraulic integrity or service life of the well. Such deformations can result from geomechanical loading, thermal loading or formation movement. Common deformation modes that geothermal wells may experience include collapse, sinusoidal or helical buckles, transverse or inclined shears, and parts. As illustrated in Figure 1, a number of these deformation modes, which are common to both oil and gas and geothermal wells, are shown. The images of the collapsed, buckled and sheared casings were measured in actual wells using MFC logs and analyzed with the 3D approach described in this paper (i.e., with the aspect ratio of the lateral and radial displacements magnified to visualize the measured deformations).

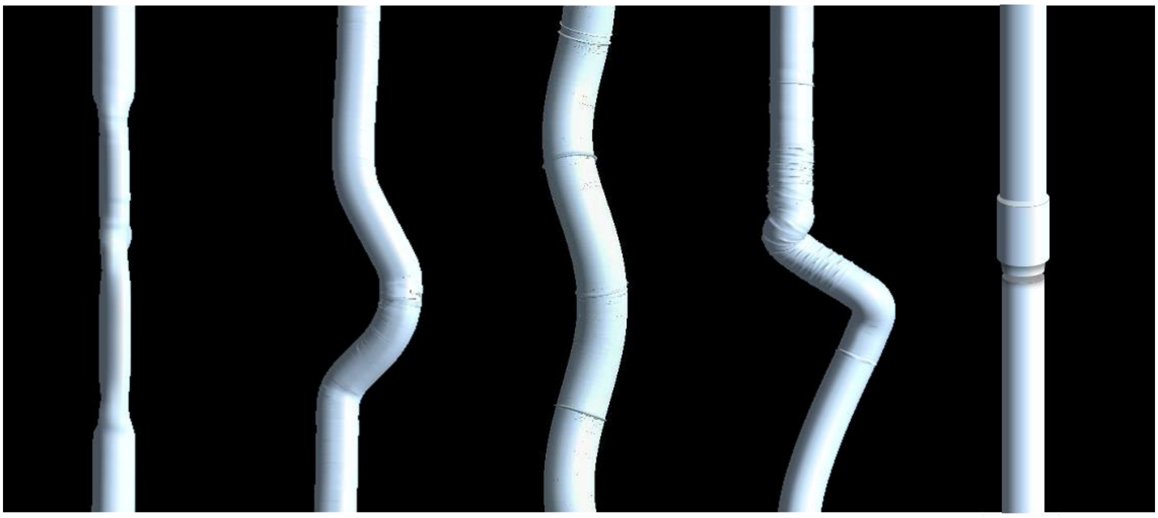



**Figure 1: Common Tubular Deformation Modes Observed in Oil & Gas and Geothermal Applications**

The characteristics and causation mechanisms of these deformation modes are documented in the literature across a wide range of wells and applications in the oil and gas and geothermal sectors. Many of the causation mechanisms experienced in the oil and gas industry parallel those occurring in geothermal operations; for example, formation subsidence resulting in casing buckling and shears noted above. A summary of the typical root causes, underlying mechanisms, observed deformation characteristics, and references documenting the collapse, shear, buckle and parted tubular deformation modes is presented in Table 1.

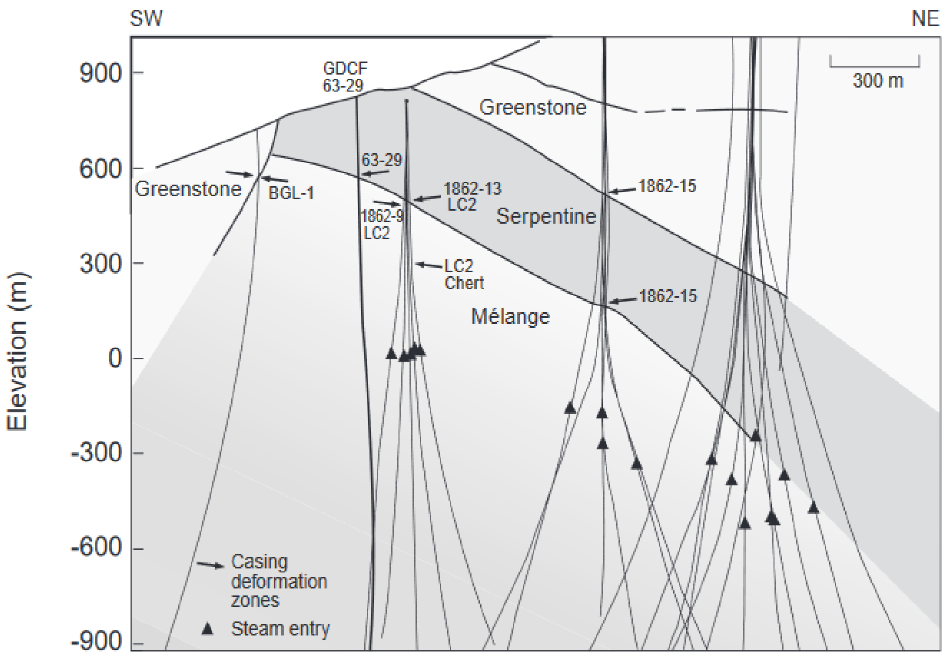
**Table 1: Summary of Tubular Deformation Modes, Root Causes, Mechanisms, Characteristics, and Related Papers**

| Deformation Mode | Root Cause(s) | Mechanism | Characteristics | References |
|---|---|---|---|---|
| **Collapse** | - External pressure<br>- Tubular collapse resistance exceeded | - Trapped annular pressure<br>- Formation squeeze<br>- Overpressure during stimulation (hydraulic fracturing) or operation | - Ovalization<br>- Minimal lateral offset | - Lentsch (2015)<br>- Last et al. (2002)<br>- Wagg et al. (1997) |
| **Parting** | - Axial tension<br>- Material yield point exceeded and/or brittle fracturing (e.g. embrittlement)<br>- Thread jump | - Tensile loads exceed parting capacity (pipe body or connections)<br>-Axially restrained thermal contraction<br>- Formation subsidence | - Reduced diameter (necking)<br>- Minimal lateral offset<br>- Parted connections and tubular bodies<br>- Thread jump-out | - Southon (2005)<br>- Xie (2009)<br>-Wagg et al. (1997) |
| **Shear** | - Lateral differential formation movement<br>- Susceptible weak layer or formation interface/transition and shear loading | - Stress changes within the overburden and/or reservoir due to volume, temperature, and pressure changes, or solids movement<br>- Tectonic activity | - Lateral offset<br>- "S" shape | - Bruno et al. (1992; 2001)<br>- Dusseault et al. (2001; 2011)<br>-Peng et al. (2007)<br>-Li et al. (2006)<br>- Wagg et al. (1997) |
| **Buckling** | - Axial compression<br>- Lack of lateral support | - Thermal Expansion<br>- Formation subsidence<br>- Uncemented channels/zones | - Lateral offset and buckled length<br>- Sinusoidal ("wave") or helical ("corkscrew") shape | - Bruno et al. (1992; 2001)<br>- Dusseault et al. (2001; 2011)<br>- Li et al. (2006)<br>- Wagg et al. (1997) |

As noted in the literature [Dale et al. (1996)], shears are generally the most problematic deformations as the local trajectory changes inhibit tool passage and restoring access is difficult and costly with conventional techniques (i.e. milling).

### 2.2 Examples of Reported Wellbore Deformations in Geothermal Wells

Review of the literature reveals that casing and liner deformations have been observed in a number of geothermal projects, spanning a wide range of application conditions, project and well ages, well designs and geographic locations [Zahacy (2018)]. Lentsch et al. (2015) examined the Molasse Basin in Germany and found four casing 'failures', representing 10% of the wells, in the region after a 10-year life. Two of these failures were attribute to Trapped Annular Pressure (TAP), the third due to either buckling or TAP, and the other to 'tectonic collapse'. Southon (2005) examined the types, mechanisms, and frequency of casing/wellbore failures in geothermal fields in the Southeast Asia-Pacific region and found failure rates ranging from 4-22% based on the completion type. The deformations were classified as TAP or parted casing; shears and buckles were not classified as a failure mechanism. Large completion sizes (10.75" and 13.375" outer dimeter) were more susceptible than 'regular' sizes (9.625"). Allan et al. (1998) examined The Geysers field in California and identified 50 wells with casing deformation in the then Unocal portion of the field. The reduced casing diameters and doglegs were believed to be the result of formation movement along fault plane and weak interfaces. Allan et al. (1998) noted that it was not determined whether shears or buckles were the dominant mechanism of deformation. With an estimated 380 wells in The Geyser field at the time [Williamson (1999)], this number suggests that approximately 13% of the wells were deformed. Pressure depletion in The Geyers field has resulted in subsidence, correlated with induced seismic events and wellbore deformations, as noted by Rutledge et al. (2000). Rutledge et al. (2000) noted that, in one region of the field, the locations of the casing deformations coincided with mapped fault planes, as shown in Figure 2, and that the observed deformations were "over short depth intervals where the wells intersect the upper and lower contacts of a serpentine unit dipping to the northeast". Rutledge et al. (2000) highlighted that one well, GDCF 63-29 shown in Figure 2, "was plugged and abandoned because of the severity of wellbore collapse concentrated at the base of the serpentine, at 244 m (800 ft) depth". It is suspected that the noted 'collapse' was more likely a misdiagnosed shear located at the fault interface. As is done in thermal oil recovery applications [Talebi et al. (1998)], a geophone array was installed in the region an effort to assess if detected microseismic events and their location could be correlated with casing deformation and integrity incidents [Rutledge et al. (2000)].




Geologic profile showing the well casing deformation zones association with upper and lower contacts of a serpentine unit. Profile is oriented N30E (viewing N60W). Steam entries delineate approximate top of reservoir.

**Figure 2: Section View of Mapped Faults and Co-located Casing Deformations in The Geysers Field [Rutledge et al. (2000)]**

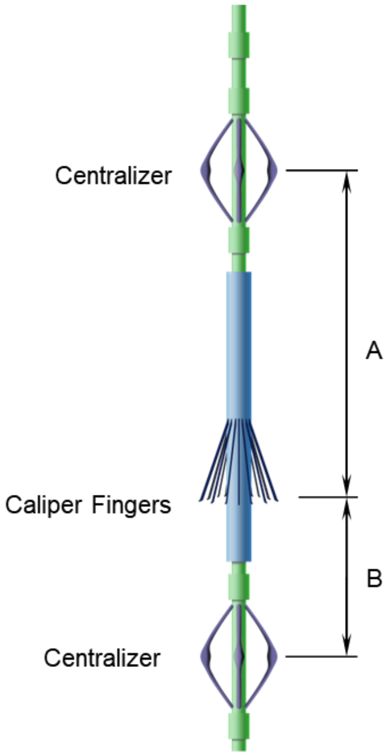
Given the reported occurrence of casing deformations in many geothermal applications and the often-misdiagnosed deformation mode, it appears that there is a need in the geothermal sector for a means of accurately identifying and quantifying deformations to support well integrity and asset risk assessments, and in order to develop appropriate mitigation and prevention strategies for these susceptible applications.

## 3. MULTI-FINGER CALIPER TUBULAR LOGGING TOOLS

MFC logging tools and analysis of the recorded data are one of many inspection methods used for assessing wellbore integrity. Other logs used for assessing the condition and integrity of wellbore barriers include: (i) tubular wall loss logs (Magnetic Flux Leakage or Ultrasonic technologies); (ii) logs used to assess cement sheath integrity and flow behind pipe (temperature logs, Cement Bond Logs (CBL), ultrasonic and geophone array acoustic logs); (iii) logs for determining coupling depth shifts, which may indicate a deformation (Casing Collar Locators (CCLs)); and, (iv) optical (camera) methods [Sveinbjornsson and Thorhallsson (2013); Kaldal et al. (2016)]. Distributed and discrete transducers of fiber-based technology for temperature (DTS), pressure, strain, and acoustic measurements (DAS) are also a part of this integrity suite.

### 3.1 Typical MFC Tool Configuration

As illustrated in Figure 3, the typical MFC logging tool that is used for assessing wellbore tubulars consists of a number of caliper 'fingers', typically 15, 24, 40, or 60 fingers (with up to 90 available for large diameters), located on the body of the logging tool, typically between relatively stiff expandable bow-spring or roller centralizers. In some applications, such as for a vertical wellbore, only one centralizer may be used. The fingers independently measure the tubular radial displacement from the tool centre using electronic sensors (e.g. Linear Displacement Sensors) or through mechanical means. Vertical resolution of MFC measurements (or the logging read frequency) can be as small as at 2 mm increments [Runciman (2019)]. MFC logging tools can be run through tubing, casing or liners on wireline, tubing, coiled tubing, or tractors. MFC's are commonly used to identify diameter and wall thickness changes due to corrosion, erosion, wear or scaling, and to identify zones of deformation or parts, such as due to external pressure, axial tensile or compressive loading or axial or transverse displacements.




**(a). Schematic of MFC Logging Tool**

**(b). Photo of a MFC Logging Tool [GoWell]**

**Figure 3: Main Components and Example of the Typical MFC Logging Tools Used to Assess Casing Wall Loss, Scale Build-up and Wellbore Deformations**

### 3.2. Limitations of MFC Logging Tools for Geothermal and High-temperature Wells

Temperature and pressure limitations of MFC logging tools are largely the result of the recording method used to measure the radial displacement of the caliper fingers, which may be either through electronic sensors or mechanical means. Today, many MFCs use electronic sensors, which allow for the recording of individual finger measurements. These tools were initially designed for the oil and gas industry where, in most applications, the subsurface temperatures and pressures allow for the use of conventional electronics. As these electronic components are some of the most sensitive components of the tools and can be rapidly degraded or may even fail at elevated temperatures, these components are often placed within a heatshield or Dewar flask for logging temperatures above 150°C, and can typically deliver between four to 12 hours of operating time at 300°C [Ásmundsson et al. (2012)]. Many advertised electronic MFC's have a pressure rating from 100 to 140 MPa. In order to run these tools without exceeding temperature limitations in geothermal applications, the well must either be cooled, potentially inducing significant tensile stresses and potential integrity concerns (i.e., in constrained wellbore tubulars due to thermal contraction), or the logging run must be performed quickly at the risk of damaging the tool or resulting in temperature-related measurement errors.

One approach to run MFCs in higher temperature wells is to use mechanical MFCs, which are rated up to 315°C. Some of these mechanical-type caliper tools are advertised as functioning at "unlimited" working pressures [Runciman (2019)]. A drawback for some mechanical MFC logging tools is the limited information that can be recorded, as some designs only capture the maximum and/or minimum finger readings, which provides extremely limited information regarding the tubular cross section. For example, in the casing inspection caliper surveys run in geothermal wells presented by Buñing et al. (2005) and Lejano et al. (2010), such max-min 60 arm MFC logging tools were run. While the authors suspected casing deformations at several intervals, the mode was not postulated, and it would not have been possible to conclusively determine the deformation mode from only the max-min MFC data. Currently, there are a limited number of advertised mechanical MFCs which are capable of recording individual finger measurements at temperatures above 300°C. As noted by Ásmundsson et al. (2012), new MFCs, and associated integrity tools are required that are rated for long term geothermal usage. MFC tools with increased temperature capability will be required as the industry moves towards more challenging geothermal environments, such as deep EGS projects [Fridleifsson et al. (2016)], and supercritical applications at temperatures in excess of 400°C, such as the Iceland Deep Drilling Project (IDDP) [Dobson et al. (2017)] and the Newberry Volcano Project in Oregon [Cladouhos et al. (2018)]. Tracking and ensuring long-term well casing integrity in such high capital cost projects will be of critical importance to the technical and eventual economic implementation of such step-out geothermal projects.

## 4. THREE-DIMENSIONAL LOG DATA ANALYSIS

### 4.1 MFC Trajectory Algorithm and Lab Validation

As shown in Figure 4, conventional MFC log analysis relies on 2D cross section recordings of radial measurements as a function of measured depth. While this data can provide an indication of radial restrictions that may be associated with a deformation, there is no indication of changes to the tubular axis. Based only on the 2D data, it is difficult to determine if the deformation mode is a buckle, a shear or due to external pressure collapse, since all of these modes can result in similar local casing ovalizations. The local 3D trajectory of the tubular, combined with radial measurements, is required to differentiate the deformation modes.

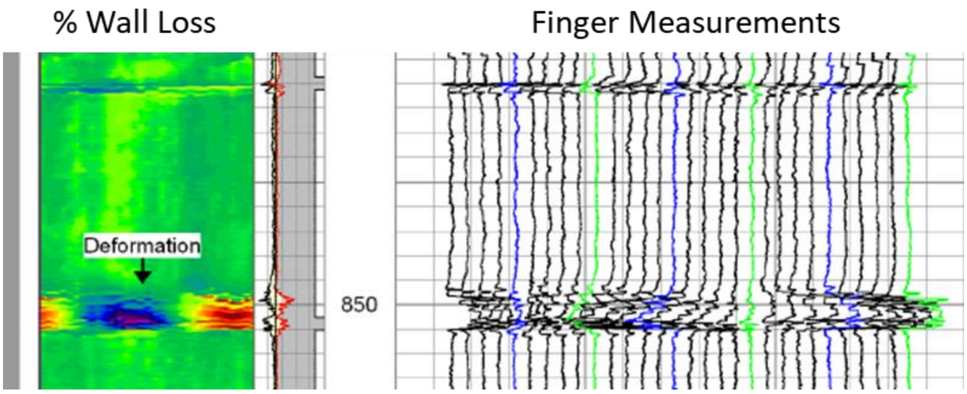
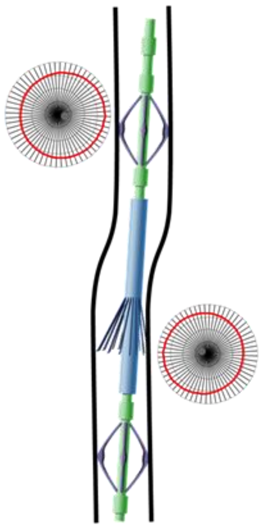
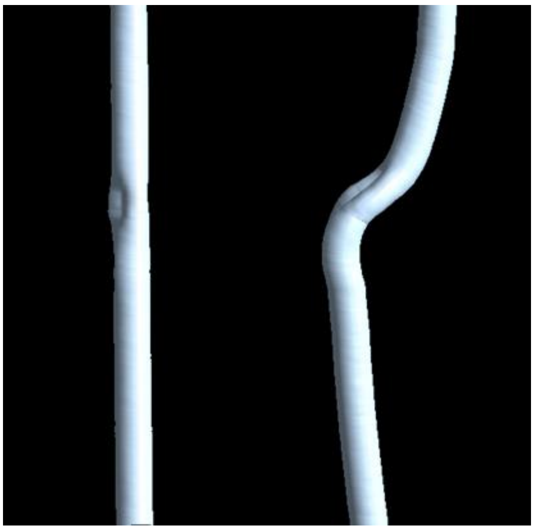



**Figure 4: Example of a Caliper Arm Traces from a Conventional Two-Dimensional MFC Logging Tool with Deformation Signature**

As MFC tools do not directly measure the tubular trajectory, a calculation approach must be applied to the data, such as a Caliper Trajectory Algorithm (CTA) described by Wagg et al. (1997), to convert the 2D log data into a 3D profile and deformation measurements. When either of the centralizers or the fingers pass through a curved tubular section, the axis of the logging tool becomes eccentric to the axis of the wellbore. This eccentricity and its direction (relative to the high-side of the logging tool) can be determined from the caliper finger measurements. By combining the physical tool dimensions - and in particular the distances from the section where the fingers are located to the upper and lower centralizers (Dimensions A and B in Figure 5) - with the radial caliper finger measurements, the local 3D shape of the wellbore and curvature can be obtained. When this 3D trajectory information is determined at each reading station and is assembled over a length of the wellbore, the orientation and 3D trajectory of the tubular and the deformed shape can be generated [Xie et al. (2016)]. Figure 5(a) displays a schematic illustrating the MFC being pulled through a deformed section of a tubular (a local shear) and section views of how the caliper fingers respond to the location of the tool (the measured eccentricity). Figure 5(b) also shows a section of a well that appears to show a region of collapsed casing (left image) generated using the conventional 2D visualization approach applied to MFC log data (straight casing on the left) versus the shape generated for the same MFC log data using the 3D calculation approach (right image) which appears to be a highly localized shear deformation. As with the deformations shown in Figure 1, the radial and lateral displacements were magnified relative to the axial dimension in Figure 5(b) for visualization proposes.



**(a). MFC Tool Eccentricity in Deformed Tubular**

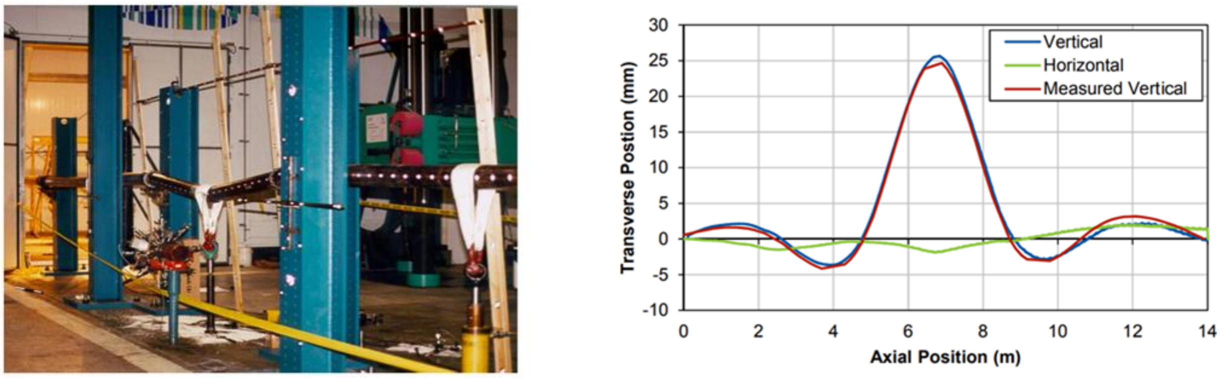


**(b). Two-Dimensional versus Three Dimensional Deformation Representation**

**Figure 5: MFC Tool Response in Deformed Well and Visualization of the Conventional versus Three-Dimensional Calculation Approach**

The 3D trajectory generated using an algorithm, such as the CTA described above, provides insights into the deformation mode and allows for the quantification of lateral shift, curvature, and estimation of drift diameter (e.g. the diameter that a tool of a specified length could pass through without deflection). If the MFC is capable of recording the 'high side' of the tool (the circumferential orientation of the tool relative to the gravity vector), and the tool inclination, when the local 3D shape of the wellbore obtained from the processed MFC log data is combined with the directional survey of the well, the local deformed shape of the casing can be oriented and mapped over the global trajectory of the wellbore. This is particularly useful when analyzing multi-well or pad-wide deformations (e.g. large-scale shear deformations impacting multiple wells at a common interface, such as along a weak bedding plane or on a fault, such as across the wells in The Geysers field shown in Figure 2).

The CTA calculation method was verified through full-scale lab testing, which involved pulling an MFC logging tool through a section of casing that was deformed into a controlled, known 3D shape [Wagg et al. (1997)]. Ten casing deformations, representing a variety of modes and displacement magnitudes, were used to assess the accuracy of algorithm. An image from the verification test and comparison of the calculated to measured trajectories for the casing subjected to a local buckle are displayed in Figure 6 [Wagg et al. (1997)].




**(a) Algorithm Verification Testing** **(b) Calculated Trajectory Results**

**Figure 6: Three-Dimensional Tubular Trajectory Verification Testing**

### 4.2 Other Logging Methods to Examine Wellbore Trajectory and Tortuosity

Gyroscopic survey tools (Gyros) also offer a means of calculating the casing trajectory using inclination and azimuth measurements; however, the measured depth resolution of standard Gyro tools (e.g. typically on the order of about 0.3 m) may not be sufficient to capture the curvature and 3D trajectory of highly localized deformations resulting from formation movements (i.e. shears and buckles), many of which are less than one meter in length [Gronseth (1989); Talebi et al. (1998); Remmer (2013); Runciman and Zahacy (2018)]. In regions of high or local curvature, after the first centralizer has passed through the deformation the gyro may not detect any change in orientation as the body of the logging tool passes through the feature since the gyro does not measure the local ovalization or shape of the casing. As such, the deformed shape of the well may not be captured by the gyro (i.e. the interval may be flagged as a region of local trajectory change, but the cross-sectional profile of the deformed tubular will not be recorded). As such, the determination of the drift diameter cannot be obtained, or may be misinterpreted, using processed Gyro log data. Nevertheless, in cases where a global or larger-scale deformations are present, for example tubing strings subjected to helical or sinusoidal buckling, Gyro tool data can be used to quantify lateral shifting and pitch length [Suman et al. (1970].

### 4.3 Other Well Condition and Integrity Information from MFC Logs

As noted above, corrosion and erosion can result in casing wall loss in geothermal wells [Buñing et al. 2005; Lejano et al. 2010], while scale build-up can result in significant restrictions. Scale or solids accumulation in a well can be interpreted from MFC log data as apparent ovality, which may be misinterpreted as a deformation. In such cases, the presence of scale can often be distinguished from deformations by examining the measured radial cross sections with reference to the nominal casing inner diameter.

An example of a well with a localized restriction is shown in Figure 7. The change in diameter was the result of highly localized scale deposition over a three meter (ten-foot) long interval, which was identifiable by the sudden and relatively uniform reduction in diameter over the interval. The nominal inner diameter of the casing is also shown on the section view, illustrating how the reduction in diameter due to scale accumulation plots well inside the casing ID. Cross-checking with daily well workover records revealed that a 149.2 mm (5-7/8") OD bit was used to drill through the restriction, which correlated to the approximately 152 mm (6") ID hole measured by the MFC logging run. It is recommended that a thorough examination of all available information, such as production and well servicing records, be performed when investigating the nature of any deformation to prevent misdiagnosis.

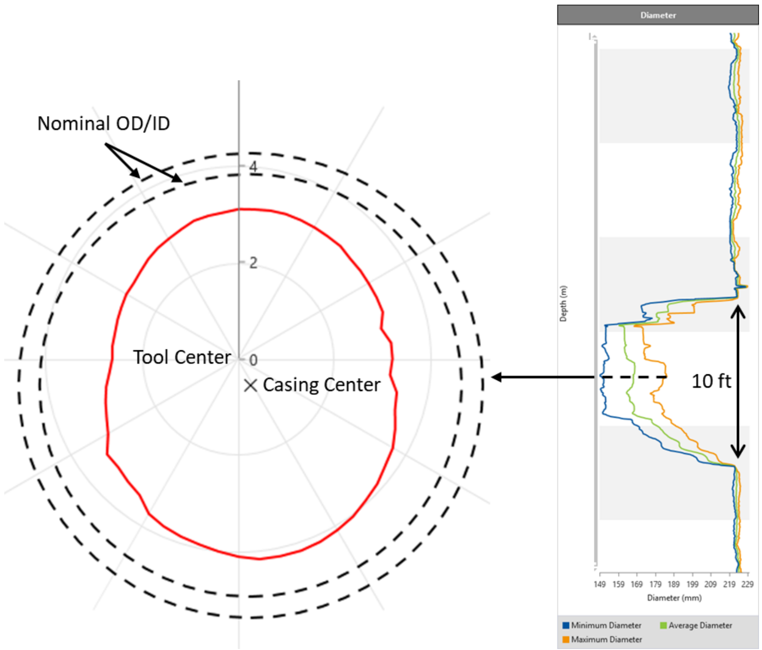



**Figure 7: Example of Scale Deposition in a Geothermal Well identified Using MFC Log Analysis**

## 5. DATA REQUIREMENTS AND CALIPER LOGGING BEST PRACTICES

There are many factors which can influence the quality of data obtained during an MFC logging tool run and the its suitability for processing using 3D analysis methods such as the CTA approach. These factors include: (i) proper tool calibration; (ii) suitable tool selection and configuration; (iii) tool running practices; (iv) data acquisition method; (v) documentation of logging tool configuration and running information; and, (vi) data post-processing. Ensuring that suitable practices are followed is crucial to obtaining accurate, reliable trajectory calculations from MFC log data. The following are the fundamental data requirements for calculating tubular shapes using a 3D MFC data approach:

1. The MFC data must not be 'corrected' for tool decentralization, as the measured eccentricity data contains the information required to transform the 2D caliper data into the 3D wellbore shape; and
2. The MFC tool geometry, specifically the distance between the measurement arms and the centralizers (i.e. Dimensions 'A' and 'B' shown in Figure 3a).

While running an MFC logging tool for the purposes of deformation analysis, it is critical to ensure the MFC logging tool moves freely in the well with its orientation dictated by any pipe deformations and not by bottomhole assembly components installed above or below the logging tool. Recognizing this objective, the following are the recommended tool configuration and running practices:

1. The MFC tool should be equipped with only two centralizers that have sufficient stiffness to keep the tool ends centralized (in particular in highly inclined sections of the well and when passing through deformations), but which allow the tool to be pulled through the tubular smoothly and with relatively low axial force (e.g. roller bow-spring type centralizers);
2. The tool should be run on wireline, and knuckle joints should be used to connect that tool to the wireline to allow the MFC logging tool to yaw, rotate and move laterally as dictated by the shape of the wellbore.
3. No other logging tools should be attached to the assembly, to allow the MFC independent movement.

There are several other recommended practices and supplemental information sources which can aid in a deformation analysis, such as inclination and relative bearing measurements from the MFC (when available). In addition to directional surveying records, supplemental information may include well drilling and completion records; well servicing and workover records; formation characterization tests and logs (such as DFITs, resistivity and gamma ray logs and FMI logs), to understand geomechanical properties, stress states and the presence of faults and weak bedding planes; the production/injection history and the operating conditions of the well and; additional casing condition and well integrity data, such as CBLs, corrosion logs, monitoring data (such as geophone and observation well data) and acoustic logs. The experience of those familiar with the well, such as well servicing and operations personnel and other subject matter experts, should also be obtained. Field operations and well servicing personnel, geologists, geomechanics engineers, asset integrity and drilling and completions personnel may also be interviewed. The comparison to baseline MFC log results and repeated logs is invaluable for tracking rates of deformation and for projecting remaining service life and potential future well integrity risks. Suitable analysis algorithms, visualization software tools and training in the processing and interpretation of MFC logs are also recommended. A full list of these recommendations and supplemental data for MFC log analysis and interpretation are provided by Runciman and Zahacy (2018).

## 6. ADVANCED NUMERICAL MODELLING USING QUANTIFIED DEFORMATION CHARACTERISTICS

Once the 3D shape and the magnitude of the deformations have been obtained, the results of the MFC log analysis can be used to gain additional insights into the underlying mechanisms responsible for the observed deformations, and possible mitigation measures can be evaluated. In cases where formation movement is interpreted as the source of the deformation, additional analyses may be used to validate estimates of formation mechanical properties or large-scale geomechanical Mechanical Earth Models (MEMs).

For example, the deformed shape and magnitude results may be used as inputs for advanced 3D, non-linear numerical models, such as Finite Element Analysis (FEA) studies which simulate tubular-formation interactions. By simulating formation movements and operational conditions, causation mechanisms can be examined to replicate the tubular shape calculated using MFC data. The simulation results can then be used to assess present and future tubular damage, for example in determining the anticipated sealing and structural capacity of nearby connections as the deformation progresses [Tao and Xie (2013)]. Such analyses require supplemental information, including: composition and mechanical properties of formation intervals, fractures and weak bedding planes/interfaces between contrasting horizons'; well construction (hole size, casing size and weight), casing and cement material properties; and operating conditions. Several published papers have examined the use of FEA and coupled wellbore-formation models for examining tubular deformations in thermal oil recovery applications [Xie et al. (1999, 2006, 2008, 2016); in subsiding reservoirs, Bruno (1992, 2001); Dale et al. (1996), Hilbert et al. (1996); and Fredrich et al. (1999)], as well as in geothermal applications [Kaldal et al. (2015, 2016)]. The schematic presented in Figure 8 shows a 'spring' model approach used to simulate the contact between the casing and formation in an FEA study examining tubular buckling (left) and shear deformations (right) [Xie et al. (2016)].

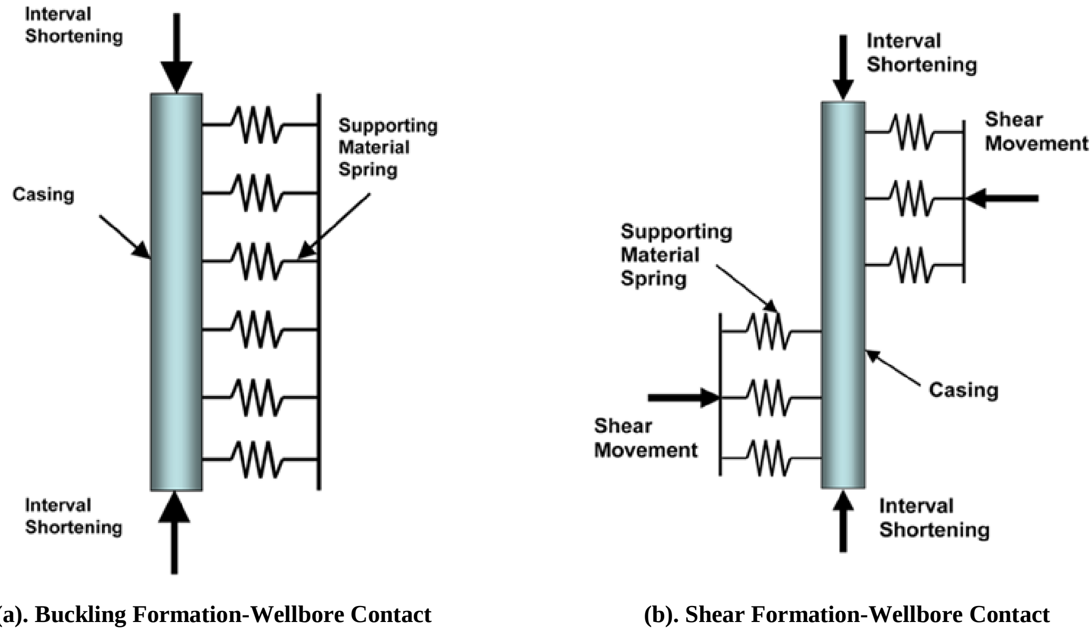



**Figure 8: Schematic of Finite Element Models for Simulation Casing Deformations**

Figure 9 displays the results of an FEA study which examined the impact of relative formation shear displacement on casing as a function of the mechanical properties of the formation and the magnitude of shear deformations. [Xie et al. (2016)]. The movement of the relatively weak, low stiffness formation (in this case, and unconsolidated sand) resulted in an elongated casing shear deformation, while the same shear displacements in a much stronger, stiffer formation (here a shale formation) resulted in significantly higher localized strain levels and curvature values in the casing. Such analysis methods can be used to both assess: (i) the accessibility to the lower section of the well, its mechanical and isolation integrity, the remaining life of the wellbore, and the corresponding risk of loss of the well; and (ii) the magnitude and direction of the formation movement, and the formation mechanical properties that would generate the observed 3D shape of the tubular. Using MFC data post-processed with a 3D visualization algorithm turns every well into a downhole strain/displacement sensor.

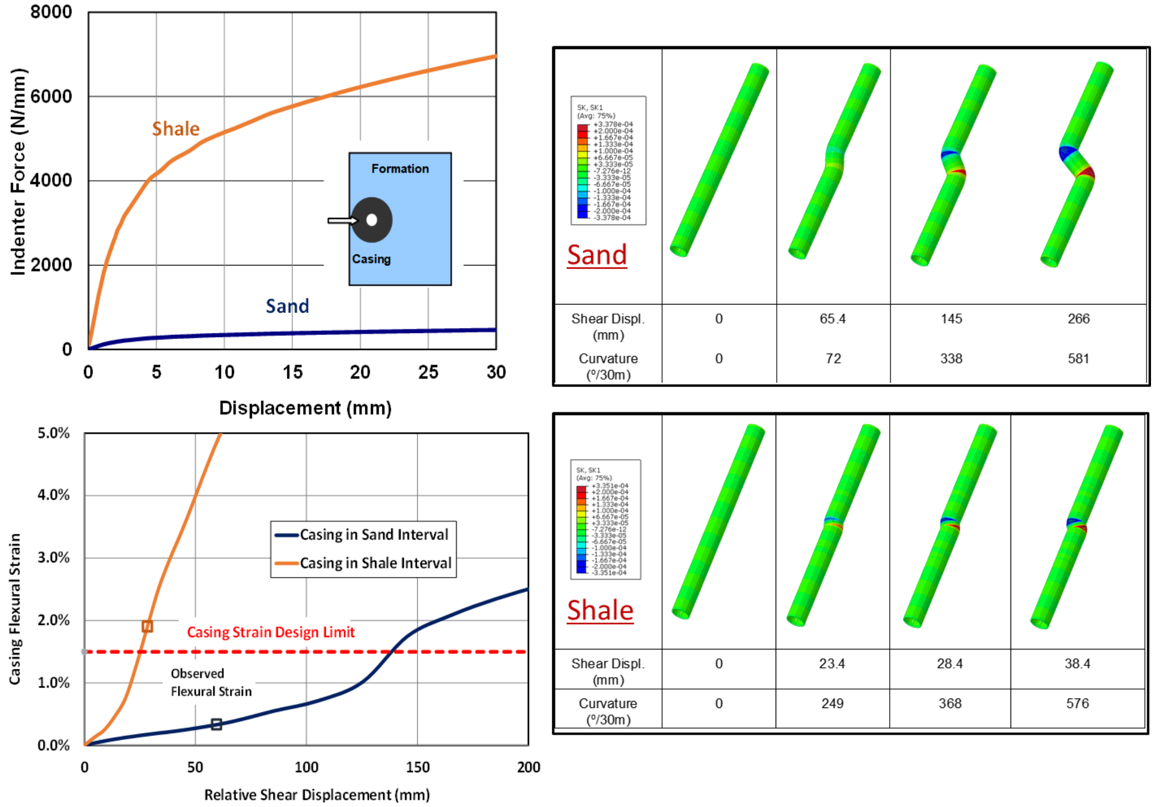



**Figure 9: Finite Element Analysis of Casing Shear Displacement in Sand and Shale [Xie et al. (2016)]**

## 7. CASE HISTORY

In preparation for this paper, a literature review was conducted and various geothermal operators were contacted in an effort to identify wells with suspected deformations that have also had MFC logs run what may be suitable for post-processing with the 3D algorithm. A number of MFC logs for geothermal wells obtained and were analyzed; however, either the logs were not suitable or the suspected deformations were obstructions due to mechanisms such as scale buildup. the case study presented here is a deformation that occurred in a steep, hard-rock application that was hydraulically fractured to stimulate the formation and create significantly larger wellbore-to-formation connectivity, much like in EGS wells.

During hydraulic fracturing operations in this application, the operator noticed that several wells suffered deformations, apparently at a common depth. The restrictions were of concern, as they impaired the ability to run other well servicing and completion equipment thorough the restrictions, and the source and root cause of the deformations were unknown. Extensive milling operations were required to restore access to the lower section in some of the wells.

Using the 3D MFC analysis approach outlined above, combined with the directional survey information, the MFC data was processed. The deformations present in the wells were determined to be transverse shears oriented in a common direction as a result of movement at a very thin, weak interface. An example image of a shear present in one of the wells is displayed in Figure 10. The deformation shown in the processed images represent somewhat less lateral movement that the formation shear due to damping of the measured deformation by the cemented pipe-in-pipe completion. Nevertheless, the identification of the orientation of the deformations showed that there was a common direction and depth across the wells in the area, and it provided insights into potential mitigation options, such as reaming a larger hole and/or modifying the mechanical properties of the cement blend. Extension of the analysis approach and the insights it provides related to the nature of the dormition, driving mechanism and potential mitigation measures is apparent. Several mitigation strategies, associated with the deformation modes noted above, are described below.

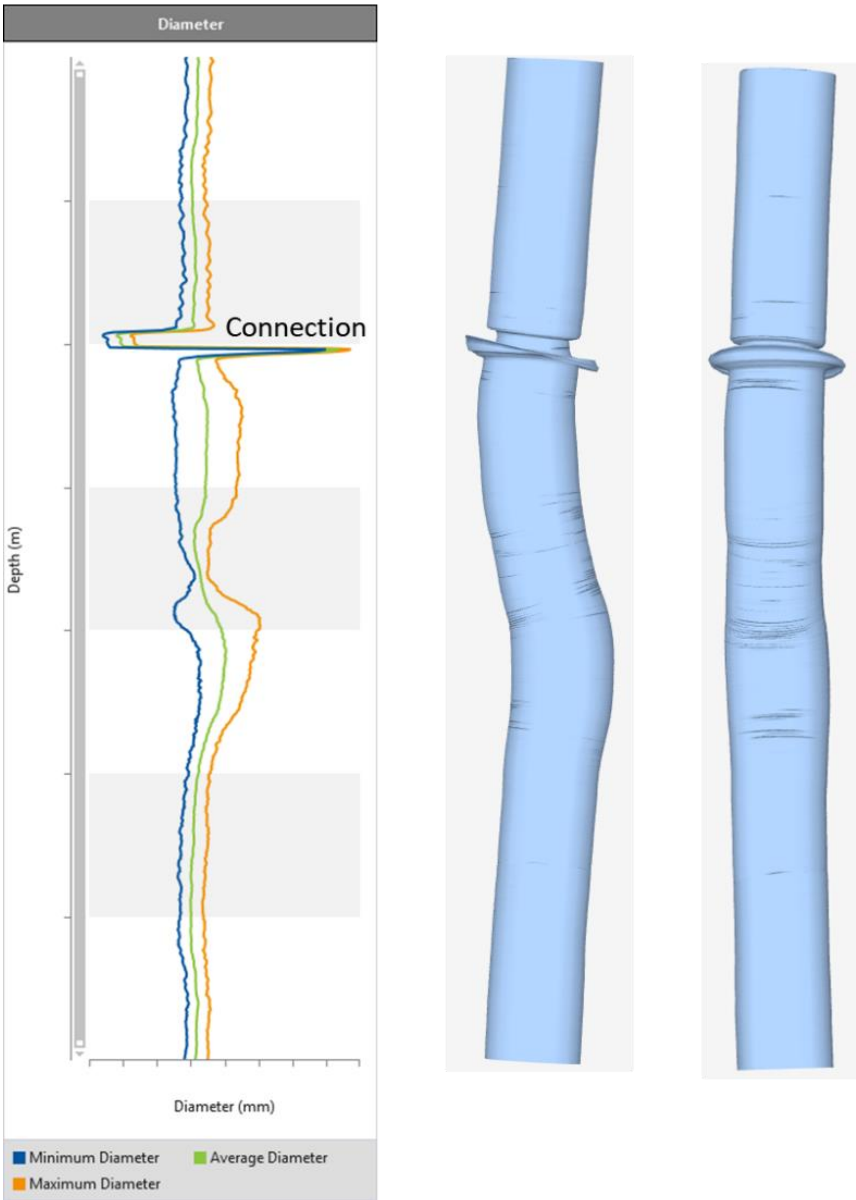



**Figure 10: Shear Deformation in a Hard Rock Formation**

## 8. DEFORMATION MTIGIATION STRATEGIES

Tubular deformation mitigation strategies are strongly dependent on the application in question, as well as the condition and age of the well, the remaining economic value of the well (e.g. the remaining resource or reserves the well may produce to the end of its service life) and associated costs and risks of potential mitigation measures. Often, the best solution combines a number of actions, including repairs or changes to the completion design or trajectory (e.g. the use of mills, wedges and reamers, bridge plugs and casing patches, inner-string tie-backs, and side-tracks), new well design and construction practices (e.g. casing size, grade and weight, locating connections relative to identified weak planes or faults, and cement selection and placement), and operational practices (e.g. modifications to fluid and pore pressure withdrawal and injection strategies). However, frequently the well has been constructed and design/construction changes are extremely limited and only practically put into practice in future or re-drilled wells. Table 2 provides a summary of some general deformation mitigation strategies. Noted references, such as those by Lentsch (2015), Dusseault et al. (2001), and Wagg et al. (1997), provide mitigation strategies for addressing damage and well failures due to collapse, parted tubing, shear, and buckling (i.e. the four deformation modes shown in Figure 1 and listed in Table 1).

**Table 2: Mitigation Strategies for Common Wellbore/Tubular Deformation Modes**

| | **Mitigation Strategy** | |
|---|---|---|
| **Deformation Mode** | **Changes to Well Design and Construction** | **Operational Changes** |
| **Collapse** | - Casing weight and collapse capacity (e.g. relative to surface casing burst capacity)<br>- Follow cement selection and cementing best practices, for example:<br>○ Casing centralization/standoff<br>○ Blend weight, free water, stiffness<br>○ Cement placement (string movement and pumping rates)<br>○ Sufficient excess cement<br>- Use of a cement blend with 'crushable' components, for example:<br>○ Hollow beads, foamed cement | - Manage temperature rate changes to allow trapped fluid to leak into formation<br>- Ensure the balance between internal tubular pressure and external formation pressure does not exceed the collapse resistance of the completion |
| **Parting** | - Use of connections with >100% pipe load capacity and suitable thermal-mechanical fatigue life<br>- Selection of a sufficiently ductile tubular material<br>- Cement placement | - Managing injected volumes, temperature and pressure cycles to prevent subsidence<br>- Manage cooldown temperature and number of thermal cycles<br>- Prevent embrittlement due to stress corrosion cracking (such as through treatment programs or blanket gas) |
| **Shear** | - Avoid drilling through susceptible slip planes<br>- No cement at susceptible depth(s)<br>- Under-ream wellbore with low stiffness cement<br>- Place connections far from known susceptible weak planes or faults | - Managing injected volumes, temperature and pressure cycles to prevent activation of a weak plane or fault |
| **Buckling** | - Follow cementing best practices to reduce uncemented intervals<br>- Apply tension preload or additional internal pressure while cementing<br>- Casing centralization<br>- Use of expansion/slip joints | - Managing injected volumes, temperature and pressure cycles to prevent subsidence<br>- Manage temperature rate changes to minimize compressive loads induced during heating |

## 9. GAPS AND LOOKING FORWARD

There appear to be a number of current and near-term technology gaps related to the MFC logging tools supplemental analysis methods for application in the geothermal sector. One such gap is the lack of widely available MFCs, and associated integrity tools, suitable for the large diameter wellbores and demanding downhole conditions of the geothermal industry, in particular MFC logging tools able withstand the high temperatures, pressures and corrosive/erosive conditions of many geothermal applications. Another gap is the apparent lack of awareness in the sector regarding the use of MFC log data to identify deformations, and additional value MFCs can provide beyond measuring wall changes or min-max diameters. Suitable MFC logging tools, data and 3D transformation algorithms can then be used to accurately identify and diagnose deformations, and data from successive logging runs can be used to track the progression of deformations, supporting risk assessments, mitigation planning and appropriate resource allocation.

## 10. CONCLUSIONS

MFC tools can provide valuable information beyond wall change measurements and the minimum diameter of restrictions. By combining the physical tool geometry with the radial finger measurements, the 3D shape of tubulars can be calculated for the identification and quantification of deformations, allowing formation-induced shear or thermal-mechanical induced buckling to be differentiated from other modes, such as collapse. At a minimum, the uncentralized MFC finger measurements and physical tool geometry is required to perform the necessary calculations. To allow the MFC tool optimal freedom of movement within the well, as dictated by any deformation, the tool should be run independently on wireline with two centralizers and a knuckle joint. The quantified tubular shape can be used as an input for advanced nonlinear numerical models, such as FEA studies, to validate the magnitude of formation movements, deformation causation mechanisms, potential mitigation options, and for the assessment of tubular damage. A deformation in a hard-rock, hydraulically fractured application was described, with the mode of deformation determined to be shear due to fracture stimulation which induced slip at a weak interface. EGS wells may experience a similar damage mechanism due to similarities in stimulation procedures. As the geothermal sector moves to more challenging applications and costly well designs, such as hot dry rock, supercritical and EGS applications, assuring reliability and availability is critical for the safe long-term operation, containment, performance and economics of these wells.

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