CRUSTAL STRESS DETERMINATION AND WELLBORE STABILITY ANALYSIS: LOS HUMEROS GEOTHERMAL FIELD CASE STUDY

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ABSTRACT

Obtaining qualitative information about the stress state in the Earth's crust is a challenging task. Typically, direct measurements of crustal stresses, all adhered to the petroleum industry, are not included in logging campaigns of deep geothermal wells, especially in high enthalpy reservoirs in which temperature conditions often exceed operational limits of the conventional logging equipment. Reliable estimations of vertical stress, minimum, and maximum horizontal stresses, as well as pore pressure are vital for ensuring safe drilling operations and geothermal fluid production. This study presents an innovative approach for the assessment of crustal stresses using non-direct stress measurements such as drilling fluid losses, mechanical caliper log, and continuously measured drilling parameters. The investigation was based on the results from deep drilling operations within the Los Humeros Geothermal Field, located at the border of Veracruz and Puebla states in Mexico, where the highest recorded temperature recorded was 395°C and hostile reservoir fluids were produced. During almost 40 years of geothermal drilling in the field, issues related to wellbore instability have been observed in multiple boreholes.

1. INTRODUCTION

Having a comprehensive geomechanical model allows addressing a series of problems related to wellbore stability during well life cycle. The applied drilling fluid pressure has a major effect on the stability of the borehole during drilling. With applied fluid pressure being lower than collapse pressure, open hole section can experience compressive failure which can lead to deformations of the wellbore wall such as borehole breakouts, as presented in Figure 1, wash-outs or even collapse of open hole section. Further decrease of drilling fluid pressure, below the pore pressure, can result in an undesirable event of drilling kick or blow-out. On the other hand, high drilling fluid pressure exceeding the fracture pressure can result in drilling-induced tensile fractures leading to partial or even total fluid losses (Pašić et al. 2007). The stable pressure window during drilling is thus localized between collapse and fracture pressure. Achieving such a delicate balance of pressures in relatively unknown systems or greenfields is a big challenge. Therefore, in order to aid mentioned problems as well as to determine safe casing setting depths, choose appropriate well completion, trajectory and cementing strategy, solid knowledge of stress state in-situ is required (Peska et al. 1995).

Underground rock formations are confined and remain under defined stress state. In-situ stresses are anisotropic, compressive, inhomogeneous and increase with depth (Gidley et al. 1989). The knowledge of the direction and magnitude of in-situ stresses is important as they control the pressure required to propagate shape, vertical extent and direction of a fracture. Within homogenous Earth, rapid and/or large stress gradient changes are not expected. The situation is however different, once cavity is created (Zoback 2007). Simplified principal in-situ stresses can be divided into minimum horizontal stress, S_{hmin}, maximum horizontal stress, S_{Hmax} and vertical stress, S_V.

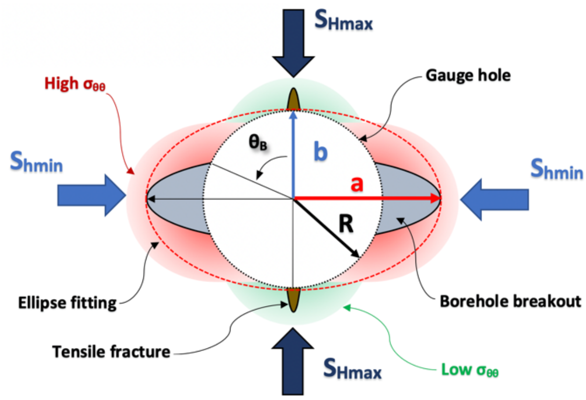

Figure 1: The breakout cross-section with acting horizontal stresses (a – semi-major axis, b – semi-minor axis, R – in-gauge open hole radius, θB – breakout angle)

Performing in-situ stress measurements at depth and under high thermal gradients is a complicated task. Due to the rather low success rate of such measurements in high-temperature geothermal reservoirs and technical limits of conventional measuring tools, these measurements are often excluded from the logging campaigns. Therefore, this study aims to predict the stress state in the Earth's crust using already available measurements carried out during drilling operations.

2. LOS HUMEROS GEOTHERMAL FIELD

The Los Humeros Geothermal Field (LHGF) is one of the four productive geothermal fields in Mexico, located at the border of Veracruz and Puebla states. The field is administrated by the Comisión Federal de Electricidad. It is a high-enthalpy field with two main distinctive feed zones, one being liquid dominant with hydrostatic pressures, located at depths between 1150 and 1800 m and temperatures ranging between 290 and 330°C. The second, steam-dominant, zone with steam-static pressures and temperatures ranging between 300 and 400°C located at depths between 2100 and 2800 m (García-Gutiérrez et al. 2009). The field consists of approximately 25 production wells with average production rates of steam of 30 ton/hour as well as several injection wells. Overall installed capacity of the LHGF amounts to 95.7 MW_e. In recent years, a significant decrease of liquid saturation is observed due to the insufficient reservoir recharge. The location of the Los Humeros caldera within the eastern Mexican Volcanic Belt (MVB) is presented on Figure 2.

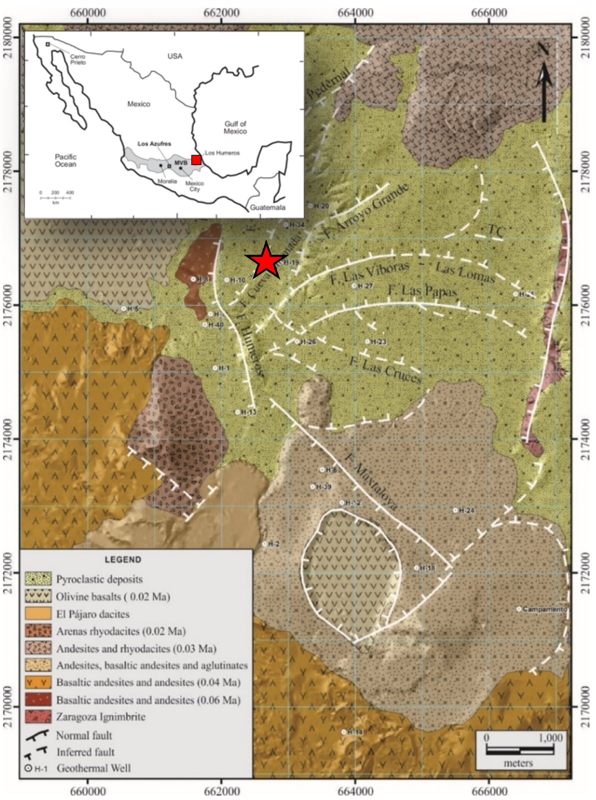

Figure 2: The location of the "A" well in the LHGF within the MVB (red square – the LHGF, red star – well "A") (adapted from González-Partida et al. 2000 and Carrasco-Núñez et al. 2015)

The investigated in this study high-temperature well "A", represented as a red star in Figure 2, is located within the central part of the Los Humeros caldera. It intersects the Cueva Ahumada fault. The well's kick-off point is located at a depth of approximately 1000 m with a horizontal displacement of 353 m, final measured depth of 2360 m and true vertical depth of 2310 m. The well was drilled from approximately 12 m to the measured depth of 1300 m with bentonitic drilling fluid with a density ranging between 1010 and 1060 kg/m^3.

3. CRUSTAL STRESS PREDICTIONS

3.1. Pore pressure

The computation of the pore pressure is not a trivial procedure. It is performed by selecting the fixed point of pressure at the pivot point, obtained from pressure logs carried out during well heating-up, and calculating the pressure using the local temperature gradient. The computation, performed using the TOUGH2 code package (Pruess et al. 2012) with a 1D vertical model, accounted for fluid phase changes, given the salinity of geothermal fluids and the CO_2 content (Grant and Bixley 2011). The formation temperature used for calculations of the pore pressure gradient is corrected using the Horner method (Horner 1951). The assumed surface temperature is an average yearly temperature at the location of the "A" well.

3.2. Vertical stress

While evaluating in-situ stresses in the reservoir it is assumed that one of the principal stresses is vertical. It is mainly by stresses generated by the gravity force are directed downwards. Assuming this, principal vertical stress can be calculated at defined well depth using the density of the particular rock formation and the gravitational acceleration constant (Zoback et al. 2007). The vertical stress component can be easily obtained from density wire-line logs, using the equation below, or through laboratory measurements.

$$S_V = \int_0^z \rho_f(z) g dz \qquad [1]$$

where,

ρ_f – density of rock formations, kg/m^3,

z – depth, m,

g – gravitational acceleration, m/s^2.

3.3. Horizontal stresses

Drilling fluid losses

Drilling fluid losses are the result of the applied total wellbore pressure (i.e. a sum of drilling fluid column and stand-pipe pressures), calculated using the equation below, exceeding the minimum horizontal stress in the open hole section, leading to its tensile failure. This assumption allows assessing the minimum principal stress at intervals of drilling fluid loss, assuming that no natural pre-existing fractures were intersected. Calculations are carried out using drilling parameters, recorded simultaneously during the drilling process. It is worth mentioning, that the circulation loss records are commonly very inconsistent and rely often on the notes made by the drilling personnel only.

$$P_W = P_{SPP} + \rho_m g z \qquad [2]$$

where,

ρ_m – density of drilling fluid, kg/m^3,

P_{SPP} – stand-pipe pressure, Pa.

The fluid loss data from three high-temperature wells within the LHGF were considered for the analysis of minimum principal stresses from the drilling fluid loss reports.

Borehole breakouts

Borehole breakouts, as presented in Figure 1, are spalled symmetrical regions at each side of the borehole wall, centred at the azimuth of the minimum horizontal stresses and located perpendicular to the maximum horizontal stresses, found in any type of formation rock and tectonic environment in which the average azimuth of the long interval section is consistent within a given petroleum or geothermal field. These enlargements of the borehole wall are caused by the failure that takes place once maximum tangential wellbore stresses exceed the compressive strength of the formation rock (Zoback 1985 and 2007). Laboratory studies made by Haimson and Edl (1972) have proven that borehole breakouts extend throughout the circumference of the borehole and their depth presents a clear increase in respect to the increase of confining pressure. These claims were later confirmed by Haimson and Herrick (1985), which concluded that the breakout width and depth are directly correlated to the magnitude of the minimum horizontal stresses.

The borehole breakouts differ significantly from other deformations such as wash-out's i.e. a 360° enlargement of the initial open hole diameter and key seats i.e. asymmetrical "one leg" spalls of a borehole wall (Zeng 2015). Different types of enlargements can be only distinguished by analysing the borehole cross-section using high-quality multi-arm caliper data. The analysis of the borehole breakouts has been widely used for the assessment of principal horizontal stress orientation at depth and various geological settings (Zoback 1985) and constraining maximum horizontal stress values. The use of borehole breakouts for the estimation of absolute stress magnitudes, from author's knowledge, has been, however, limited and not yet well described (Galera 2006 and Zeng 2015).

In order to compute orthogonal maximum and minimum open hole diameters as well as breakout orientation, the ellipse fitting method was developed. For fitting the ellipse on the mechanical 6-arm caliper measurement points obtained from the "A" well, as presented in Figure 3, equations by Fitzgibbon (1999) were applied, whereas the best fit is based on a general conic equation. The ellipse fitting method uses the least square criterion. The resulting data is used for further investigation of minimum and maximum horizontal stresses and breakout orientation. In this investigation, it was assumed that the well is perfectly cleaned from the drilling mud prior to logging.

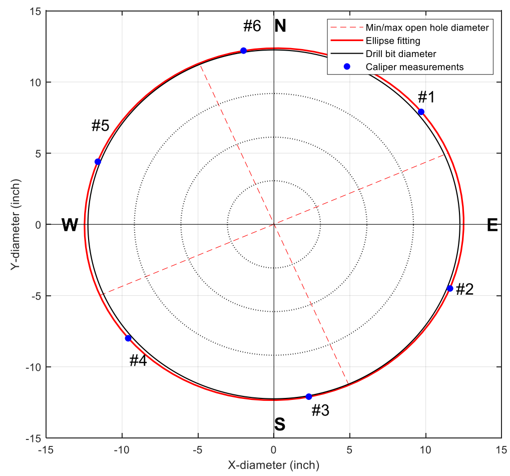

Figure 3: Results from the ellipse fitting method at a depth of 496 m in the "A" well

The developed ellipse fitting method cannot however easily discriminate between different borehole enlargements such as wash-outs, breakouts or key seats. That is due to the ellipse fitting method results being symmetrical.

3.4. Analytical model

In order to calculate the minimum and maximum horizontal stresses from the 6-arm mechanical caliper log carried out in the "A" well, a combination of theoretical equations by Kirsch (1898), Jaeger (1961) and Zoback (1985) were applied, where a cylindrical hole is considered in a thick, homogeneous, isotropic and elastic plate subjected to maximum and minimum principal stresses. Assumptions made for computations of minimum and maximum horizontal stresses include no excess pressure in the wellbore and $S_{Hmax} \leq 3S_{hmin}$, which is always the case in-situ (Brace and Kohlstedt 1980 and Zoback 2007). Equations developed by Zoback (1985) allowed expressing the cohesive strength of formation rocks at the point of intersection between breakout and the wellbore and at the deepest breakout point. Assuming that breakouts follow a trajectory along given cohesive strength of rock allowed assessing minimum and maximum horizontal stresses.

The results of research carried out by Byerlee (1978) on the friction of various rock types have concluded that at normal stress up to 200 MPa, which is the case for the conditions of the "A" well within the LHGF, shear stress required to cause sliding might be approximated by the equation below.

$$\tau_0 = 0.85 \cdot \sigma_N \quad [3]$$

The frictional sliding friction coefficient for most of the rocks are in a range between 0.6 and 1.0 (Byerlee 1978). For the case of the LHGF, a sliding friction coefficient of 0.6 was assumed. Due to a lack of laboratory measurement, a literature search on basic mechanical and elastic properties of formation rock (i.e. andesite) was carried and presented in Table 1.

Table 1: Mechanical properties of andesite obtained from the literature survey

	Value	Unit
Bulk density	2540	kg/m³
Angle of internal friction	40	°
Elastic modulus	30·10³	MPa
Poisson ratio	0.25	-
Tensile strength	12	MPa
Uniaxial compressive strength	113	MPa

3.5. Results

Figure 5 presents the computation results of crustal stresses from measurements in the "A" well within the LHGF using methods described in this study.

It can be observed in Figure 5A that well experiences strike-slip regime, based on predictions from drilling fluid losses, to thrust (i.e. reverse) faulting regime, based on predictions from borehole breakouts. From the analysis of the fluid losses during drilling in the "A" well only four pressure points for depths between 500 and 1250 m were obtained. These points stay in good agreement, or slightly below the vertical stress calculated based on rock density.

Figure 5B presents the ratio between minimum and maximum stresses in the system. It can be seen that the ratio equals approximately the $\frac{\nu}{1-\nu}$, which amounts to 0.33. This means that both crustal stresses are part of the same fracture network. It is also speculated that the fracture network present in the LHGF might potentially be a zipper fracture network (Li et al. 2017).

Figure 5C presents results from the ellipse fitting method developed in this paper. The red line represents the maximum, the blue line the minimum open hole radii, whereas the black line represents the in-gauge hole radius of 6.125 inches (0.156 m). It is noticed, that the minimum calculated open hole radius stays below the in-gauge hole radius for the first 325 m, with an exception of intervals between 500 – 550 m and 650 – 700 m, as well as in the interval between 1100 and 1225 m. The maximum computed open hole radii remain far above the in-gauge line, except intervals between 600 – 650 m and 750 – 800 m, indicating significant deformations of the open hole section.

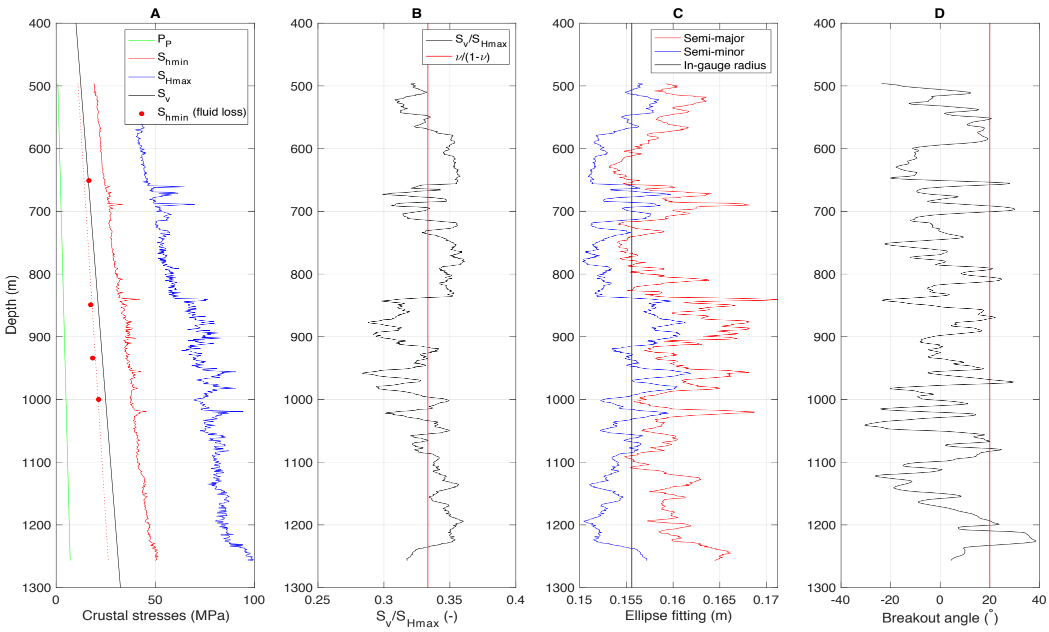

Figure 5: Results from the ellipse fitting method from the 6-arm mechanical caliper log in the 12 ¼" open hole section in the "A" well within the LHGF

Calculated borehole breakout orientation presented in Figure 5D indicated that the breakout angle in the interval between 500 and 1250 m amounted to approximately 20° (marked with a red line) in the NE direction. This is in close agreement with the studies carried out by Carrasco-Núñez et al. (2015) on the geological and structural mapping of the central part of the Los Humeros caldera, which indicated the orientation of the Cueva Ahumada inferred fault, on which well "A" is positioned, as approximately 30 – 40° in NE direction for southern part and 15 – 20° in NE direction for northern part. It should be noticed that the ellipse fitting results might potentially include borehole deformations other than the borehole breakouts such as wash-out's, where open hole diameter is enlarged in all directions. It is however evident that at depths with borehole breakouts, i.e. intervals of maximum radii being larger than the in-gauge hole and minimum radii staying in agreement with an in-gauge radius, orientation is leaning towards 20°, whereas for narrower open hole sections, orientation is closer to 0°.

The calculated crustal stresses allow also to compute the minimum injection pressures needed for an effective hydraulic stimulation operation in direction of all three principal stresses, and the best minimum injection pressure able to create a fracture network.

4. WELLBORE STABILITY ANALYSIS

4.1. Failure criteria

Borehole failure criteria refer to the way of establishing stress conditions under which borehole wall will deform and collapse (compressive failure) or fracture (tensile failure) and simultaneously lead to drilling fluid loss into the adjacent formation rocks. The stress analysis using appropriate failure criterion is the main part of the wellbore stability investigations. In this study, in order to design safe wellbore pressure for prudent drilling operations, two failure criteria were taken into consideration i.e. Mohr-Coulomb, most commonly used for brittle materials such as rocks or cement mortar, and Mogi-Coulomb (Al-Ajmi and Zimmerman 2005 and 2006). As before, the filter cake effect was omitted.

4.2. Results

It can be seen in Figure 6, that the well “A” experiences compressive failure only for the Mohr-Coulomb criterion, in the well section between approximately 850 m and 1250 m, where applied total wellbore pressure falls below the collapse pressure line. For the Mogi-Coulomb criterion, throughout the whole interval calculated collapse pressure is much lower than the applied wellbore pressure, thus no failure is expected. The compressive failure zone calculated from the Mohr-Coulomb criterion fits perfectly with the enlarged hole radius, which is regarded as a difference between the minimum radius obtained from the ellipse fitting method and the in-gauge hole radius. It can be seen that the radius difference is much greater than zero at the compressive failure interval, especially between 850 and 1100 m, indicating hole enlargements such as borehole breakouts and wash-out zones. The negative values of the collapse pressure calculated from the Mohr-Coulomb and Mogi-Coulomb criteria observed in the collapse pressure graph between 500 and approximately 750 m indicate a region in which the overpressure and rock strength decrease. Here the stability driven by the balance between rock strength and fluid pressure could be reaching the critical values at which the borehole could fail (Peska et al. 1995).

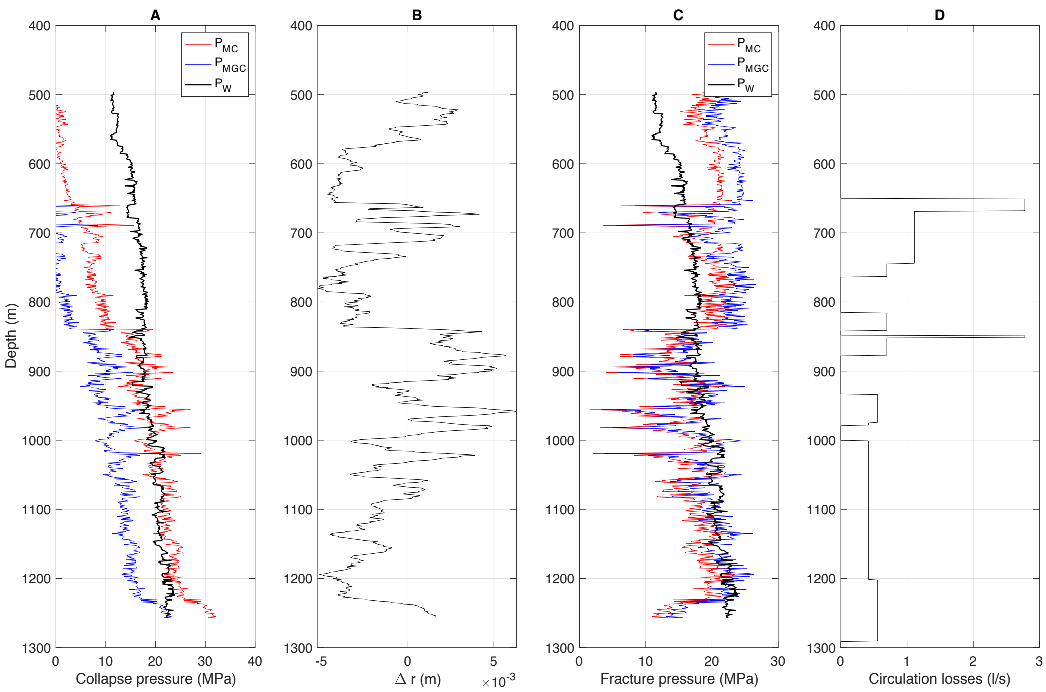

Figure 6: Computed collapse pressure (A), a difference between minimum radius obtained from the ellipse fitting approach and drill bit radius (B), fracture pressure (C) and fluid losses during drilling operations (D) in the interval between 500 and 1250 m in the well “A” within the LHGF

An interesting phenomenon was observed for the tensile failure in the “A” well. It can be seen that there are two distinct zones of tensile failure where wellbore pressure exceeded calculated fracture pressure during drilling, for the Mohr-Coulomb as well as for the Mogi-Coulomb criterion, i.e. between depths of 675 and 700 m and interval between 850 and 1250 m. These potential tensile failure zones are in perfect agreement with the drilling fluid loss zones encountered during the drilling of the “A” well and registered by the drilling personnel, which confirm the possibility of the tensile failure.

Calculations were also carried out for the shear stresses and shear failure in the “A” well for both the Mohr-Coulomb and the Mogi-Coulomb criteria. It was, however, proven that in the investigated interval, shear stresses stay far below the shear failure line at all times along the well depth, meaning that no shear failure occurs. Such failure is not common for brittle rocks, common for the LHGF, but for more plastic and ductile rock formations such as shales, clay or soil.

5. CONCLUSIONS

This paper presents methods of crustal stress state predictions based on in-direct stress measurements acquired from drilling parameters, circulation fluid losses and results from multi-arm caliper wire-line campaign. The fresh approach on the determination of principal crustal stresses from the 6-arm caliper recordings, based on the developed ellipse fitting method, proved to be successful. However, it cannot easily discriminate between different, especially asymmetrical, borehole enlargements, due to the ellipse fitting results being symmetrical.

The computed stress state allowed to carry out wellbore stability analysis for drilling operations carried out in the “A” well within the LHGF and establishing safe pressure window. Results from this research could be used in the casing and cement design procedures, well trajectory optimisation, safe pressure window selection and operational pressure design for the future geothermal wells within the LHGF.

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