Delineation of Shallow Fault Damage Zones by Analyses of Drilling Loss Zones: A Case Study from the Olkaria East and North-East Geothermal Fields, Kenya

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ABSTRACT

Fault zones are primary controls on permeability architecture, fluid circulation, and heat extraction in high-enthalpy geothermal systems hosted in volcanic terrains. In the Olkaria East and North-East geothermal fields of Kenya, these zones are characterized by intervals of intense fracturing that are routinely intersected during drilling operations. This study presents a systematic analysis of drilling fluid and circulation returns loss zones recorded in 32 geothermal wells to delineate shallow fault damage zones and assess their spatial distribution, geometry, and structural controls. The loss zones are interpreted as zones of enhanced permeability associated with fault-related fracture networks.

Correlation of loss intervals with lithological logs, well trajectories, and regional structural trends shows a strong spatial association between the loss zones and the N-S (Oloolbutot fault & Olkaria fracture), ENE–WSW (Olkaria fault), and NW–SE striking faults and fractures, which constitute the dominant structural fabric of the Olkaria Volcanic Complex. Statistical analysis indicates that 70–75% of all loss zones in the sampled wells occur at depths shallower than 300 m. Loss zone thicknesses range from <20 m to >500 m, with the thickest zone at OW-51A having an 800m loss zone. Lateral continuity of loss zones across adjacent wells (e.g., the 742, 731, and 710 well clusters) supports interpretation as coherent fault damage zones rather than isolated fractures. The results demonstrate that drilling loss data provide a cost-effective, high-resolution dataset for characterizing shallow structural permeability and refining fault models in active geothermal field development.

1. INTRODUCTION

Fault damage zones represent regions of distributed deformation surrounding fault cores, characterized by elevated fracture density, altered rock properties, and enhanced permeability relative to the host rock (Shipton et al., 2002; Faulkner et al., 2010). In volcanic-hosted geothermal systems, such zones often serve as principal conduits for hydrothermal fluid flow and are critical to reservoir productivity (Rowland & Simmons, 2012; Moeck, 2014). However, direct imaging of these features at reservoir scales remains challenging due to limitations in seismic resolution and other conventional geophysical methods, particularly in the shallow subsurface (<1 km) where velocity contrasts are low and near-surface scattering is pronounced.

Drilling operations provide an alternative source of high-resolution subsurface data through the observation of circulation loss events. Total or partial loss of drilling fluid and drill cuttings occurs when the wellbore intersects highly permeable or fractured intervals capable of accepting large fluid volumes, commonly associated with fault damage zones (Bjornsson, 1996; Ármannsson et al., 2015). While usually treated as operational hazards due to drilling challenges and uncertainties, systematic documentation and analysis of loss zones offer a valuable indicator for subsurface permeability structure.

This study investigates the utility of drilling loss data for delineating shallow fault damage zones in the Olkaria East and North-East geothermal fields, located within the Olkaria volcanic complex. The objectives are threefold:

(i) to map the depth distribution, thickness, and frequency of drilling loss zones;

(ii) to evaluate their spatial correlation with known fault orientations and structural trends; and

(iii) to assess the applicability of loss zone analysis as a method for structural permeability characterization during geothermal field development.

2. GEOLOGICAL AND STRUCTURAL SETTING

The Olkaria geothermal system is situated within the central segment of the Kenya Rift, approximately 120 km northwest of Nairobi. It is hosted in the Quaternary Olkaria Volcanic Complex, which comprises dominantly rhyolitic lava flows and pyroclastic deposits on the surface, trachytes with basaltic and tuff intercalations, and minor felsic intrusions (Goff et al., 1991; Omenda, P.A., 1998; Omondi et al., 2016).

The structural pattern of the greater Olkaria volcanic complex area is characterized by the following fault trends: the Ol-Njorowa gorge, the N-S trending Oloolbutot fault & Olkaria fracture, NW-SE, NNW-SSE, ENE-WSW Olkaria fault, and the ring structure(Lagat et al., 2005; Omenda, 1998; Riaroh & Okoth, 1994). These faults are undoubtedly considered to have a substantial effect on the geothermal fluid flow systems of the area.

Productive geothermal wells in the area are preferentially located near these structural intersections, underscoring the role of fault architecture in controlling reservoir behavior.
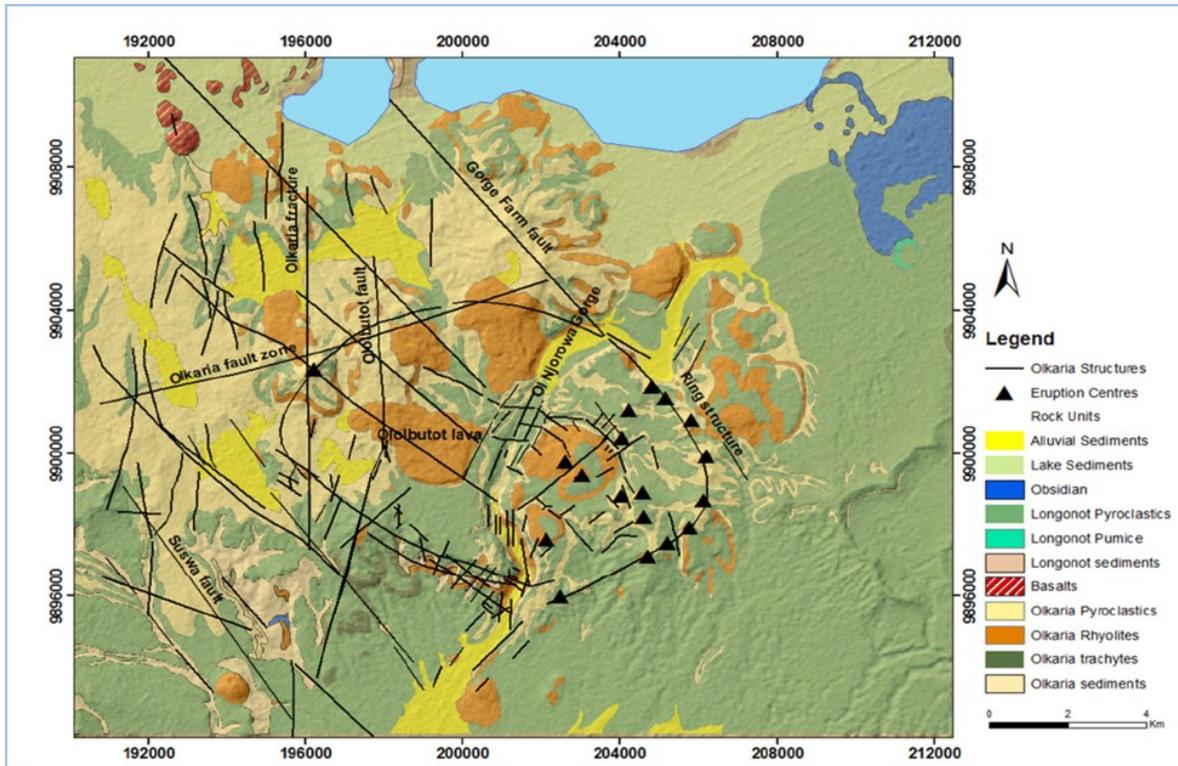

Figure 1 Geological and structural map of Olkaria Volcanic Complex (adopted from Clarke et al., 1990; Munyiri, 2016).

Figure 2 below shows the location of the study area with the sampled geothermal wells and their trajectories. The geological structures of the area have also been appended, showing their general strikes and positions relative the the wells.
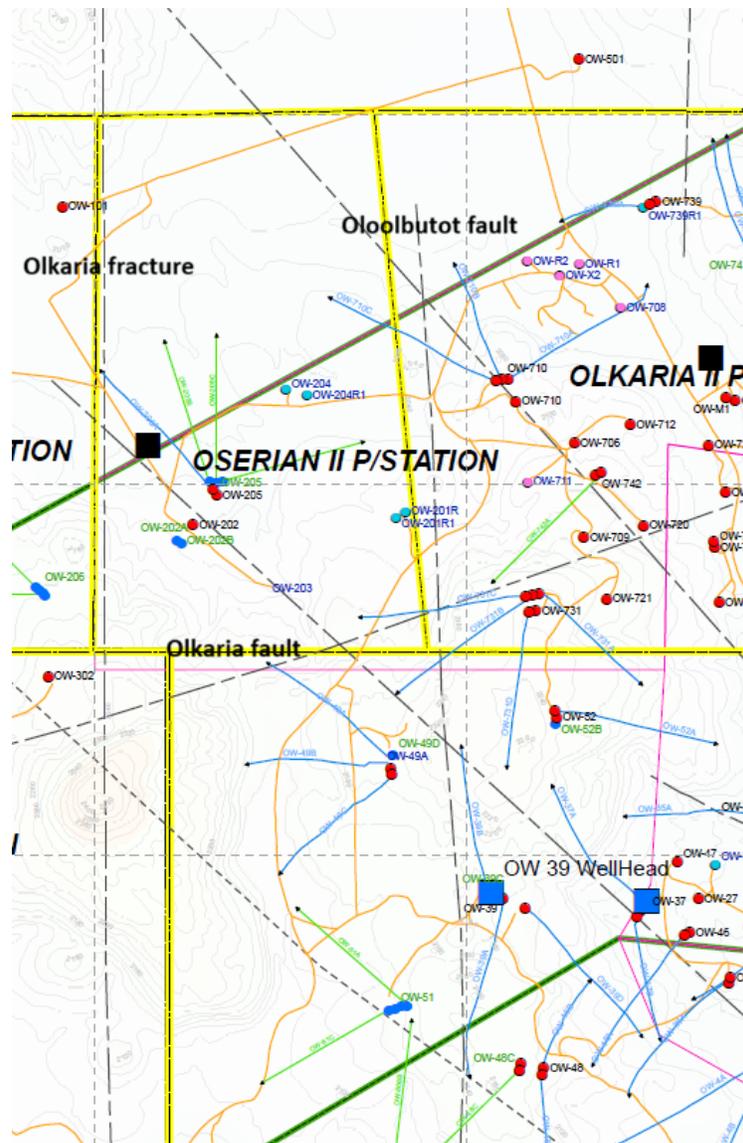
Figure 2 Location map of the study area with the appended geological structures.

3. DATA AND METHODOLOGY

3.1 Dataset

The analysis is based on drilling reports from 41 geothermal wells drilled in the Olkaria East and North-East fields (Table 1). For each well, depth intervals of partial or total circulation loss were extracted from daily drilling and geological logging reports and compiled into discrete loss zones. A total of 41 loss intervals were identified across the dataset. Supporting data include lithological logs, alteration descriptions, deviation surveys, and existing structural maps derived from surface mapping and seismic interpretation.

Table 1: Summary of wells and loss zones used in the study

Well Name	Loss zone from	Loss zone to	Loss zone thickness
49A	542	1034	492
39	76	292	216
39A	762	800	38

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731	218	290	72
731	316	716	400
731A	188	332	144
731B	254	330	76
731C	252	334	82
731D	514	562	48
731D	632	1084	452
710	58	242	184
710A	22	306	284
710B	290	372	82
710B	790	850	60
710C	26	90	64
710C	114	128	14
204	62	256	194
204R	94	162	68
204R	404	490	86
48B	156	306	150
48B	318	380	62
46	778	1030	252
205	68	366	298
205A	68	114	46
48	84	410	326
48A	0	92	92
48C	454	540	86
742	28	314	286
742A	26	298	272
52	332	410	78
35A	78	306	228
35A	390	516	126
51A	112	460	348
51A	508	1308	800
37A	106	298	192
39B	0	48	48
39D	30	58	28

36	0	72	72
36	84	332	248
36A	278	296	18
45C	250	296	46

3.2 Modeling

From the borehole geological reports, a geological model was produced using RockWorks17 modeling software.(Figure) From this geological model, cross-sections and profiles were produced and used in the visualization of the subsurface geology.
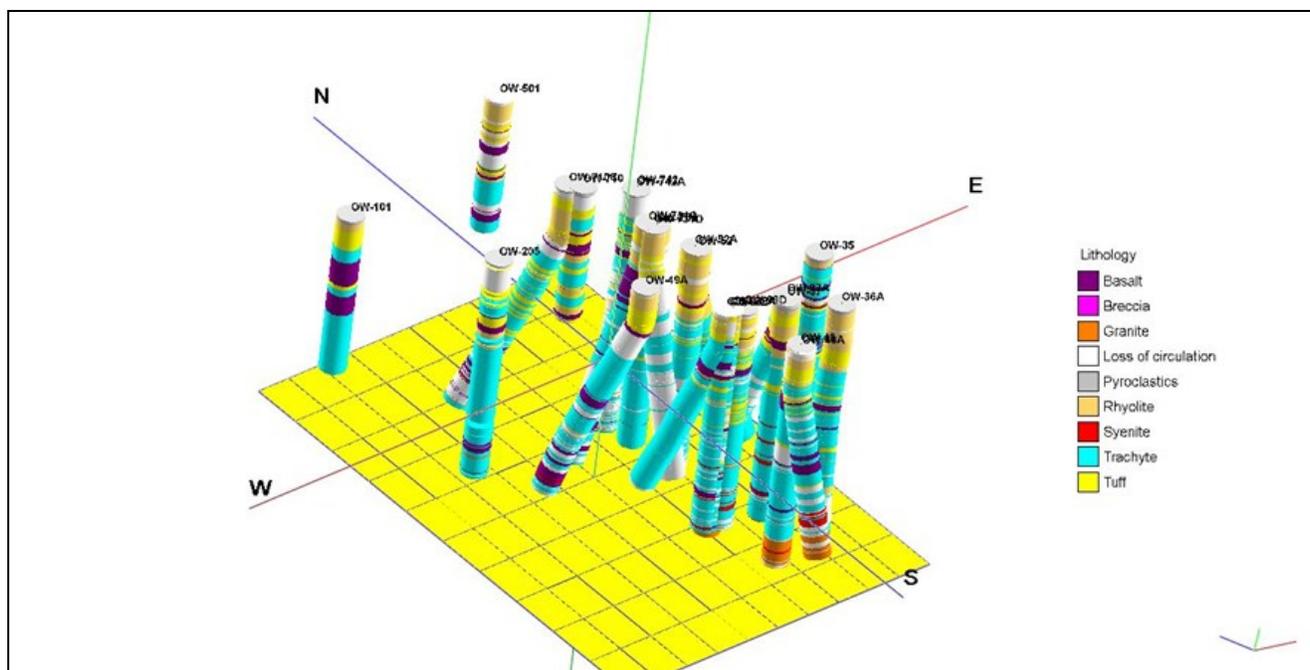

Figure 3 Striplogs of some of the wells with drilling losses

3.2 Analytical Approach

Each loss zone was defined by its top and base depth, from which the thickness was calculated as:

$$T = Z_{base} - Z_{top} \tag{1}$$
where

T is thickness (m), and Z denotes depth below surface (m).

Loss zones were analyzed for:

- Depth distribution and thickness,

- Spatial clustering across adjacent wells.

Spatial correlation was assessed by comparing loss zone depths and lateral positions of neighboring wells projected onto common cross-sections oriented parallel to dominant fault trends. Zones exhibiting consistent depth alignment and lateral continuity over distances of 200–500 m were interpreted as expressions of the same fault damage zone.

4. RESULTS

4.1 Depth Distribution and thickness

The majority of loss zones occur in the shallow subsurface. Of the 41 recorded intervals, 38 (73%) are located above 300 m depth. Losses below 500 m are less frequent but exhibit greater persistence along the wellbore e.g., Well 51A (800 m), 49A (492 m), 731D (452 m). These loss zones can also be associated with the major NW-SE striking faults, the Oloolbutot fault, and the Olkaria fault.

4.3 Spatial Patterns and Structural Correlation

Strong lateral continuity is observed in multiple well clusters. In the 731 cluster (Wells 731, 731A–731D), overlapping loss zones between 188 m and 334 m suggest intersection with a single, ENE–WSW trending damage zone, aligning with the Olkaria fault. Similarly, the 710 and 742 clusters (Wells 710, 710A–710C, and Wells 742 & 742A) exhibits correlated losses from 22 m to 372 m, aligned with a NW–SE structure.
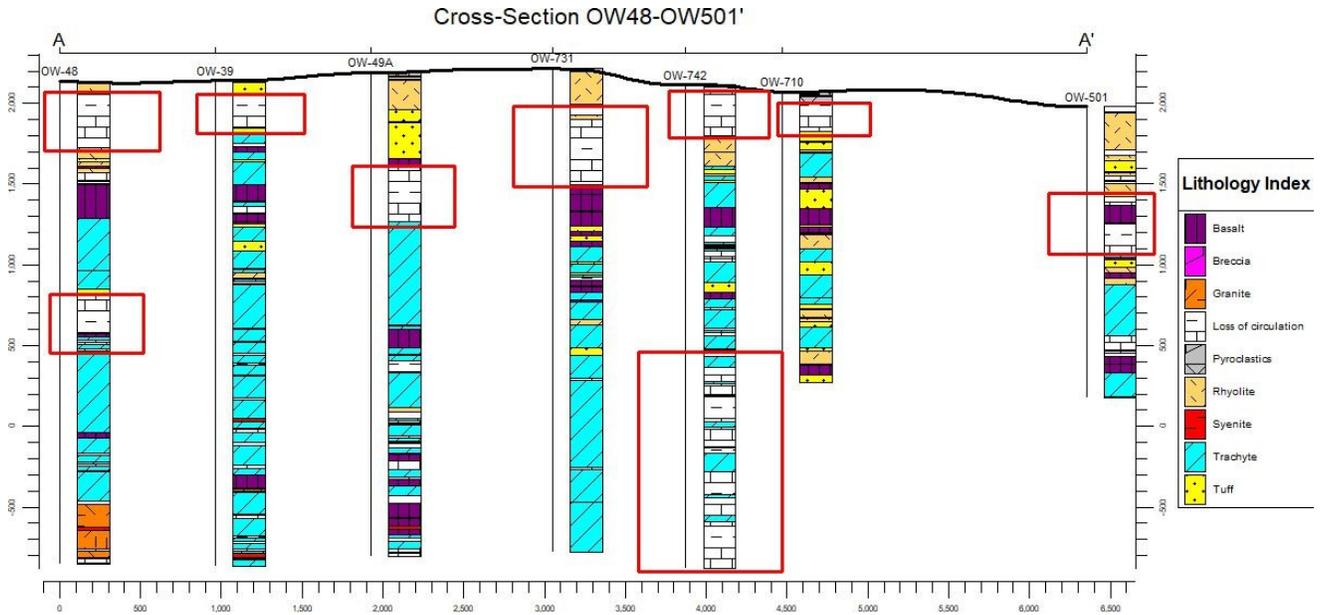
Figure 4 Striplogs from OW-48 to OW-501 (N-S) following the general trend of Oloolbutot fault. The loss zones are shown in red rectangles.

5. Discussion

5.1 Fault Damage Zones as Permeability Controls

The spatial and statistical association between loss zones and dominant fault trends confirms that shallow permeability in Olkaria East and North-East field is structurally controlled. The observed thickness variability reflects differences in fault displacement, host rock competence, and degree of fracture connectivity which are key parameters governing damage zone width (Schultz et al., 2008). Thicker loss zones (>300 m) likely correspond to mature fault systems with wide damage envelopes, whereas thinner zones may represent subsidiary fractures or tip-line damage.

The concentration of losses in the upper 300 m suggests that shallow faulting remains active or has been recently reactivated, consistent with ongoing rifting in the Kenya Rift. This shallow damage zone network provides a critical component of the reservoir's permeability architecture, facilitating vertical and lateral fluid migration.

5.2 Implications for Reservoir Characterization and Drilling Operations

Drilling loss data offer a high-resolution, cost-effective means of constraining fault damage zone geometry where geophysical methods are unreliable. Integration of loss zone maps into structural models can improve well targeting, reduce drilling uncertainty, and inform casing design.

From an operational standpoint, early identification of shallow damage zones enables proactive mitigation of circulation loss risks, including optimized mud formulation, staged cementing, and strategic casing setting depths. Conversely, in production and reinjection

planning, these zones may be deliberately targeted to access naturally fractured, high-permeability intervals without hydraulic stimulation.

6. Conclusions

Drilling fluid loss zones serve as reliable indicators of fault damage zones in volcanic geothermal systems and can be systematically used to infer structural permeability.

In the Olkaria East and North-East fields, loss zones are strongly correlated with N-S, ENE–WSW and NW–SE trending normal faults, confirming the dominant role of these structures in controlling fluid pathways.

The majority (70–75%) of loss zones occur at depths <300 m, with a modal depth range of 50–250 m, indicating that shallow fault damage is widespread and hydrologically significant.

Loss zone thickness varies from <20 m to >500 m, with thicker zones associated with major fault strands, reflecting differences in fault maturity and host rock properties.

Spatial clustering of loss zones across adjacent wells demonstrates lateral continuity consistent with fault damage zone geometry, supporting their use in structural mapping during field development.

This approach provides a practical framework for integrating operational drilling data into geomechanical and reservoir models, enhancing both exploration efficiency and development sustainability in geothermal systems.

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