A Comparison of Alteration Mineralogy and Measured Temperatures from Three Exploration Wells in The Fiale Caldera, Djibouti

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Keywords

Alteration mineralogy, drilling, temperature logging, East African Rift, Fiale Caldera, Djibouti

ABSTRACT

Alteration mineralogy can be indicative of current reservoir temperatures and provide a valuable guide for drilling decisions. Alternatively, when alteration mineralogy does not appear to reflect reservoir temperatures, it may misguide drilling decisions. The cause of a mismatch between alteration temperatures and measured temperatures may be related to changes in reservoir conditions that have not yet produced alteration minerals in equilibrium with the conditions. The observed alteration mineralogy may be a relic of prior reservoir conditions. This work compares the measured temperatures attained through wireline logging to the alteration minerals observed in the analysis of cuttings from three exploration wells in the Fiale Caldera.

1. Introduction

Three full sized directionally deviated wells, Fiale-1 (F-1), Fiale-2 (F-2), and Fiale-3 (F-3) were drilled to depths of around 2000 meters (true vertical depth, TVD) as part of a geothermal exploration project in the Fiale Caldera, within the Asal Rift region of Djibouti (Figure 1). These wells were drilled as part of the Fiale Caldera Exploration Drilling Project sponsored by Electricite de Djibouti (EDD). Drilling was performed by Iceland Drilling Company, the temperature-pressure logging was performed by JRG, the mud logging was provided by geologists from KenGen supported by intern geologists from Office Djiboutien de Developement de l'Energie Geothermique (ODDEG) and Centre d'Etude et de Recherche de Djibouti (CERD).

The project was managed by EDD Project Management Unit of which Mohamed Chaari is the Project Director and Jalludin Mohamed is the Technical Director. Geologica Geothermal Group is providing on-going technical and project oversight for drilling and well testing.

Figure 1: Location of Fiale exploration wells and Asal-5 (A-5), an offset well drilled outside the caldera.

During drilling, cuttings were collected approximately every 3 meters and observed under a binocular microscope. In addition, the abundance of smectite type clay was indicated using the methylene blue test (Harvey, 1993). Upon the completion of drilling, temperature and pressure (±spinner) logs were run by wireline as part of completion tests after a heat-up period. While additional analysis of the cuttings is ongoing, the field observations of alteration mineralogy will be discussed in this work. Temperatures indicated by alteration mineralogy are then compared to the temperatures measured in the wells.

2. Geology and Lithology

The geologic setting of the Fiale Caldera is characterized by its tectonic location in a young active rift zone, the Asal Rift. The Asal Rift has been the object of geothermal exploration since the late 1970's (e.g. Zan et al., 1990; D'Amore et al., 1998, Houssein and Axelsson, 2007). The geologic and geophysical setting of the Fiale Caldera is described in detail in Doubre, 2004 and Doubre et al., 2007 a, b. Volcanic rocks from the Fiale Caldera wells range from fresh to altered basalts, aphanitic to porphyritic intermediate volcanic rocks and rhyolites.

The Fiale exploration wells were directionally drilled northeast, southwest and west across the main northwest structural trend of the extensional rift zone. The wells were spud in the lava lake, within the caldera. Except for the thick rhyolite layers encountered deep in the Fiale caldera

wells, the lithologies were similar to that observed in well Asal-5, a vertical well drilled in 1987 several hundred meters outside the caldera (Khaireh, 1987).

The generalized lithology is presented in Figure 2.

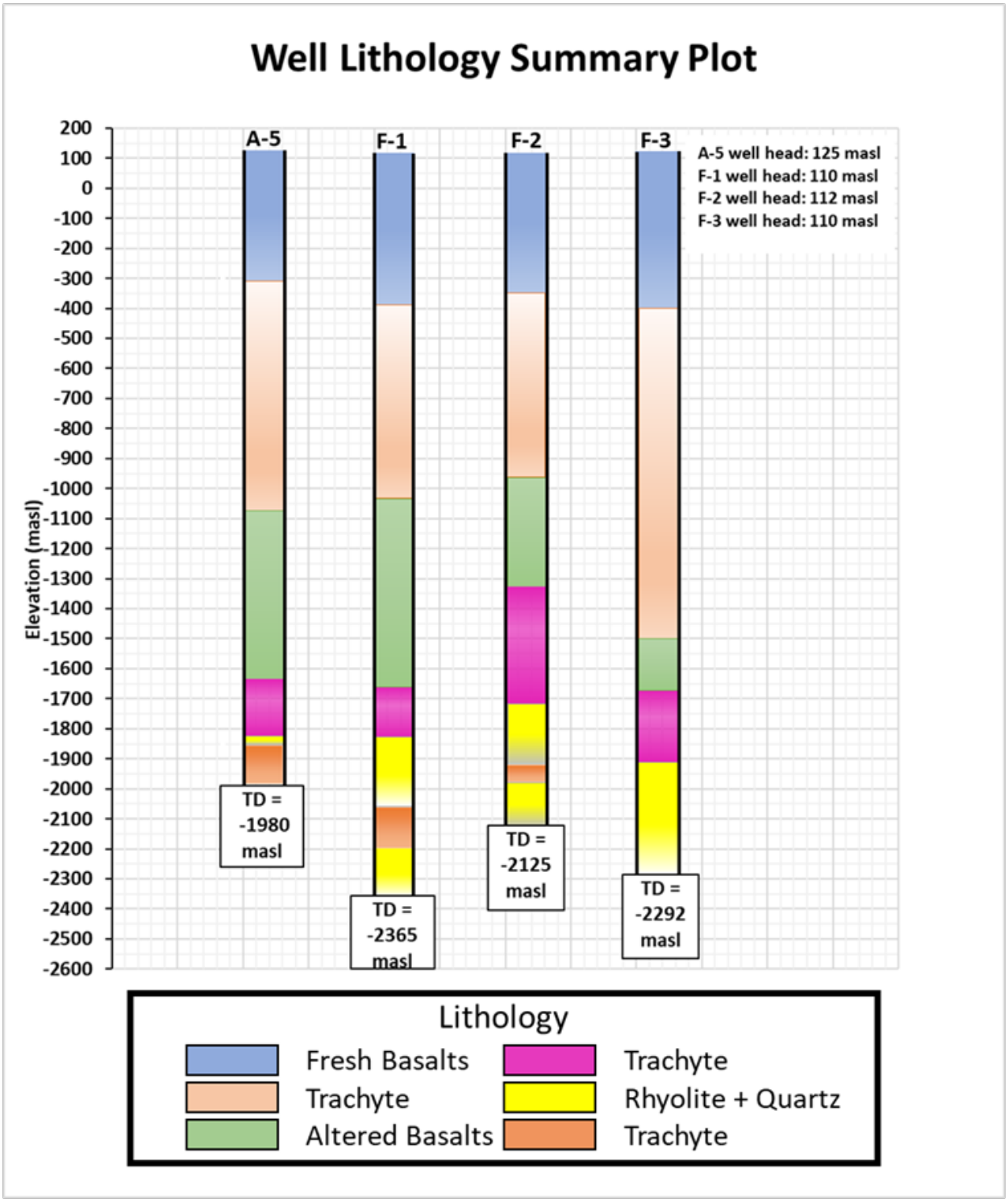

Figure 2: Summary of lithologies encountered in Asal-5, Fiale-1, Fiale-2, and Fiale-3.

3. Alteration Mineralogy

The alteration observed in the wells included many common geothermal alteration minerals: smectite, quartz, wairakite, chlorite, pyrite, epidote and actinolite. This paper will focus on epidote and actinolite, two high-temperature readily recognizable minerals (Figure 3) indicative of temperatures of approximately 250°C and approximately 300°C, respectively (Browne, 1978). Among the three wells, the shallowest depth epidote was observed was at 783 meters while actinolite was observed as shallow as 1220 meters.

In addition to high temperature minerals, the occurrence of smectite, a low temperature alteration mineral typically indicative of temperatures <180°C, is also assessed. A smectite cap, common in volcanic hosted geothermal systems, forms a low permeability zone between 50 and <180°C. In each of the three Fiale wells, temperatures occur within this range at three depths: above the shallow hot zone (400 to 550 m TVD), between the shallow hot zone and cold zone (750 to 900 m TVD), and below the cold zone (1500 m TVD). However, smectite only occurs to depths around 650 m TVD and is not present in the deeper zones of similar temperature.

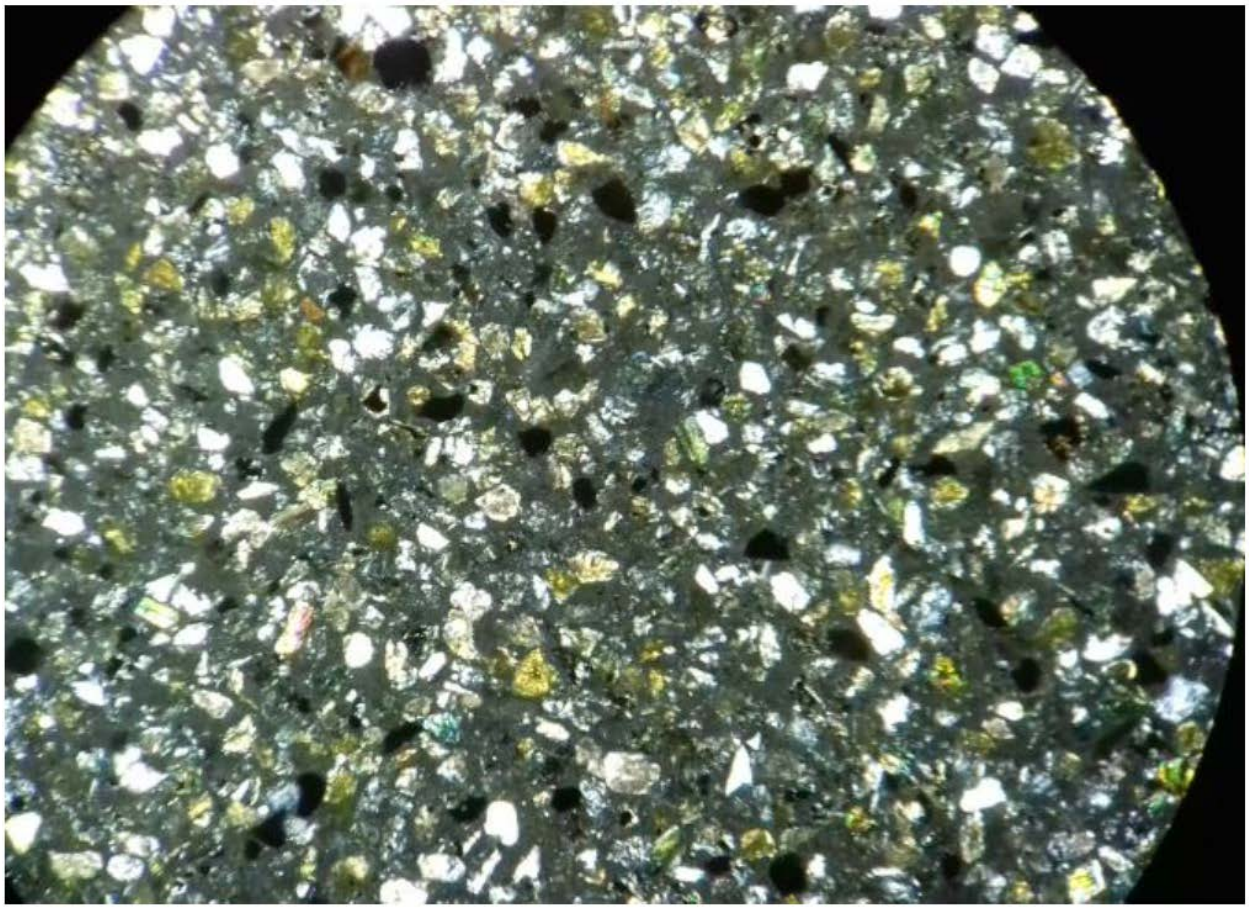

Figure 3: Thin section from 1508 m MD in Fiale-2: note both epidote (green crystals) and actinolite (pale yellow crystals). The measured temperature at this depth was <100°C. Thin Section photo courtesy of Nima Mousa at CERD.

3.1 Fiale-1 Alteration

The alteration mineralogy observed in the first exploratory well (Fiale-1) were:

Surface to 200 m TVD: Unaltered Zone

200 – 870 m TVD: Argillic – smectite and white clay minerals ± hematite, replacement calcite

870 – 1365 m TVD: Epidote + titanite + calcite

1365 – 2482 m TVD: Actinolite

3.2 Fiale-2 Alteration

The alteration mineralogy observed in the second exploratory well (Fiale-2) were:

Surface to 165 m TVD: Unaltered Zone

165 – 790 m TVD: Argillic - smectite and white clay minerals ± hematite, replacement calcite

790 – 1220 m TVD: Epidote + prehnite + quartz + calcite

1220 – 2409 m TVD: Actinolite

3.3 Fiale-3 Alteration

The alteration mineralogy observed in the third exploratory well (Fiale-3) were:

Surface to 114 m TVD: Unaltered Zone

114 – 783 m TVD: Argillic - smectite and white clay minerals ± hematite, replacement calcite

783 – 1574 m TVD: Epidote + prehnite + quartz + calcite

1574 – 2246 m TVD: Actinolite

4. Temperature Logs

Temperature logging revealed a shallow hot zone with temperatures exceeding 150°C, an intermediate cool zone with temperatures as low as 70°C and a deep hot zone with temperatures exceeding 350°C; this general temperature profile was detected in all three exploratory wells. For each well a temperature survey after at least one week of heat-up are available.

4.1 Fiale-1 Temperature Logging

After completion of drilling, multiple temperature surveys were performed inside the drill pipe with the well uncased from the bottom of the 9-5/8" casing at 1189 m MD to Total Depth of 2743 m MD. A recompletion was performed to line the uncased portion of the hole. The survey performed nine days after the recompletion can be viewed below (Figure 4).

The pressure/temperature survey measured a maximum temperature of 363 687 at 2 MD. There is a notable reversal in the well, with the coldest point at 70 C just below the shoe of the

9 5/8” casing (1189 m MD) at 1246 m MD. There are several breaks in the temperature gradient from cooler zones between 1950 and 2550 m MD.

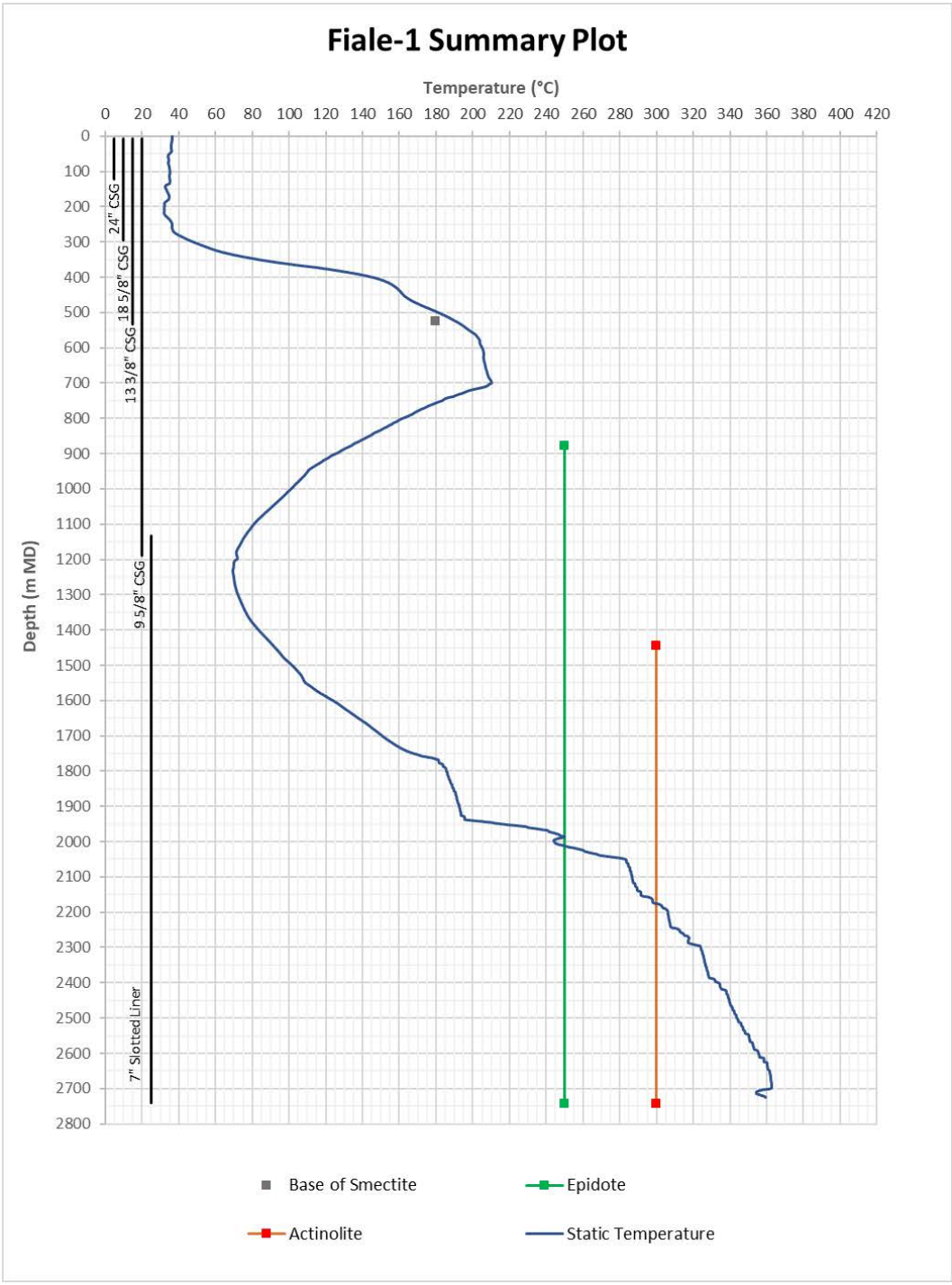

Figure 4: Summary plot showing casing design, depth of alteration mineralogy, and the measured temperature profile for Fiale-1.

4.2 Fiale-2 Temperature Logging

With approximately 4 months of heat-up after completing an injection test, a static temperature survey of Fiale-2 was completed on 09 April 2019 (Figure 5). The survey was completed inside the cased and lined hole to a depth of 2445 m MD. The maximum temperature of 352°C was recorded at the survey total depth. At the casing shoe (the top of the liner section) the temperature was 277°C.

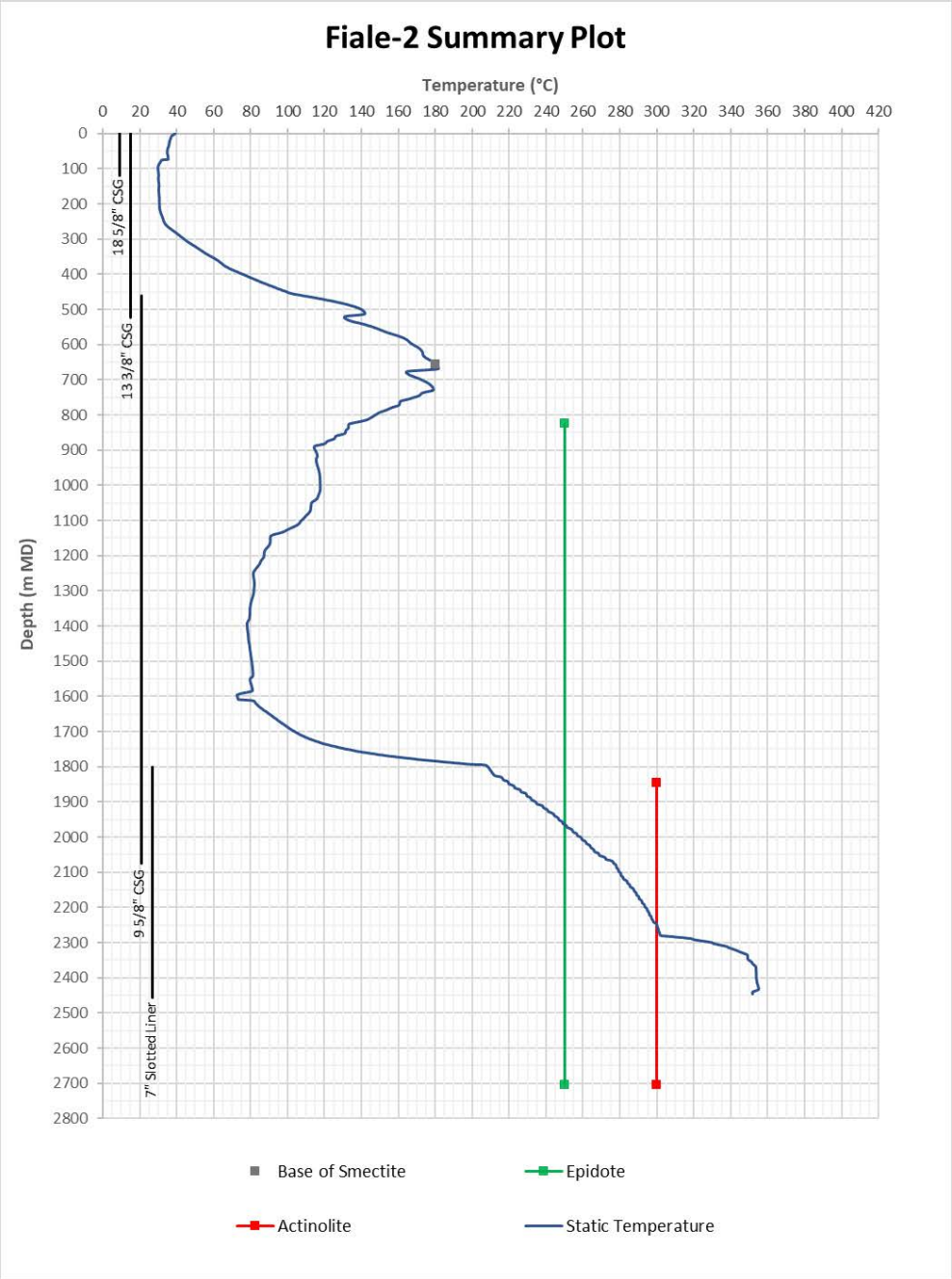

Figure 5: Summary plot showing casing design, depth of alteration mineralogy, and the measured temperature profile for Fiale-2.

4.3 Fiale-3 Temperature Logging

Approximately two months after completion testing, a static temperature survey of Fiale-3 was completed on 14 April 2019. The survey was completed inside the cased and lined hole to a depth of 2625 m MD. A maximum temperature of 362°C was recorded at the survey total depth. This measured profile is presented in Figure 6 along with the occurrence of smectite, epidote, and actinolite.

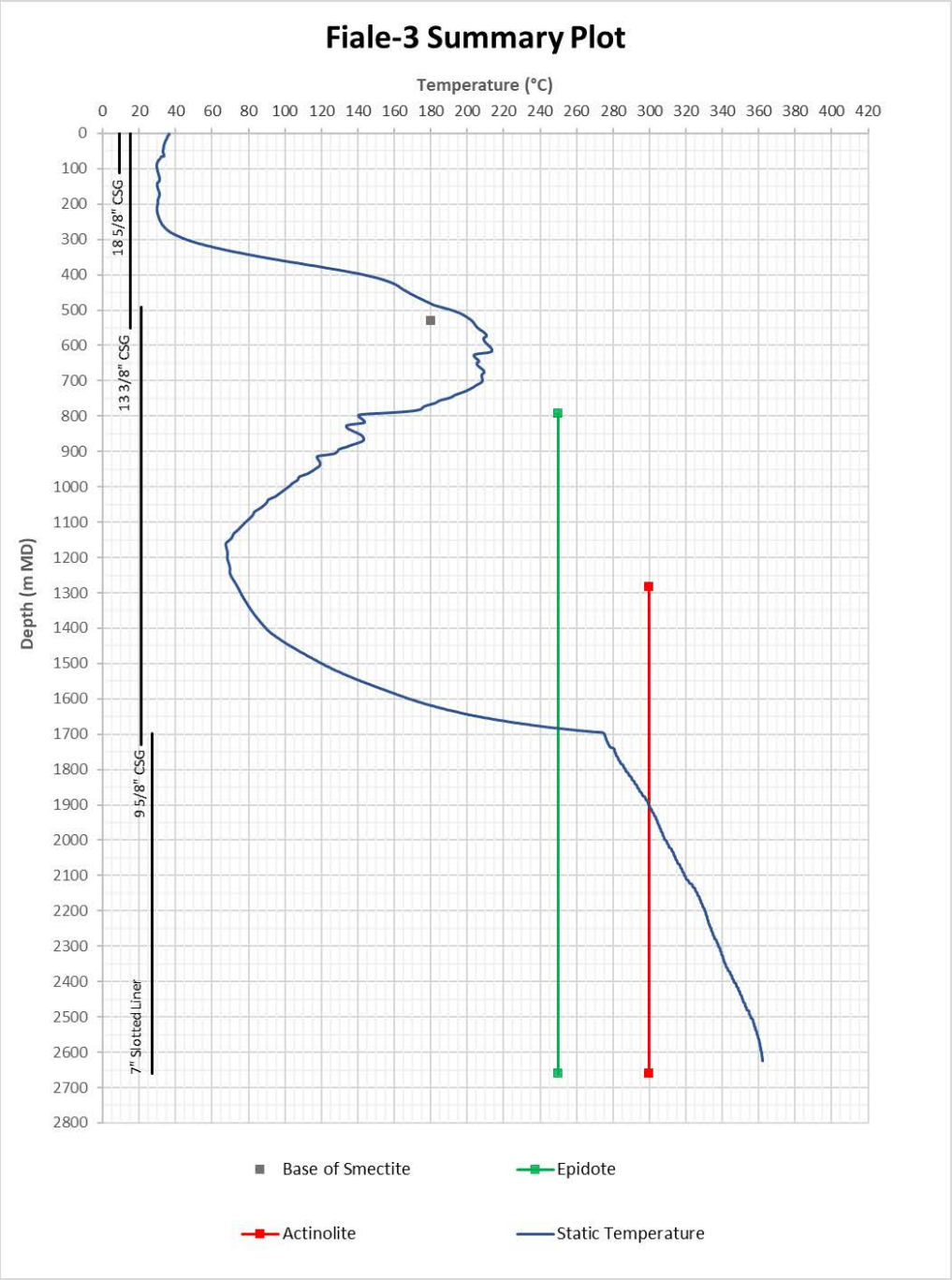

Figure 6: Summary plot showing casing design, depth of alteration mineralogy, and the measured temperature profile for Fiale-3.

5. Discussion

Alteration mineralogy can be indicative of current reservoir conditions in some geothermal fields. However, from the temperature logs of the three Fiale wells, it is clear that the high-temperature alteration minerals are not in equilibrium with present down hole measured temperatures (Table 1).

Table 1 Alteration and measured temperature summary of Fiale exploration wells.

Well	Epidote-1st occurrence (m MD)	Indicative temperature (□C)	Measured Temperature (□C)	Actinolite-1st occurrence (m MD)	Indicative temperature (□C)	Measured Temperature (□C)
Fiale-1	877	250	135	1444	300	91
Fiale-2	824	250	135	1847	300	220
Fiale-3	792	250	150	1283	300	74

Epidote forms at temperatures ~250°C. However, at the depths that epidote was first observed in the cuttings, the measured temperatures were less than 160°C in all three wells. Actinolite is indicative of rock temperatures near 300°C but the measured temperatures were less than 230°C at the depths of the first appearance of the mineral.

These discrepancies between temperatures measured and those indicated by alteration minerals indicate that the minerals are not in equilibrium with reservoir (measured or estimated) temperatures. More importantly, assuming that the minerals were formed in equilibrium with rock temperatures, temperatures were higher in the past by >200°C in the zone now known as the "cold" zone. Thus, the hydrothermal alteration could be relicts from a geothermal system with higher reservoir temperatures.

Furthermore, the hydrothermal alteration mineral smectite, characteristic of low-temperature hydrothermal alteration in volcanic terranes, does not occur in the cold zone where it might be expected.

There are not yet fluid analyses results however, the decrease in reservoir temperatures between 700 and 17000 m MD can be explained by the infiltration of cold seawater between the time the secondary minerals formed and the present. The Fiale Caldera, in which the exploration wells were spudded, is located between the Bay of Ghoubbet, a cove connected by a narrow passage to the Gulf of Tadjoura, and Lac Assal, the third most saline body of water and third lowest point on earth (Figure 7).

The lack of re-equilibration of the high- and low-temperature minerals to observed temperatures suggests that the sea water infiltration may be geologically recent. Although the epidote and actinolite discussed herein appeared fresh in the binocular microscope, additional thin section and geochemical analysis of the cuttings will enable assessment of any retrograde alteration.

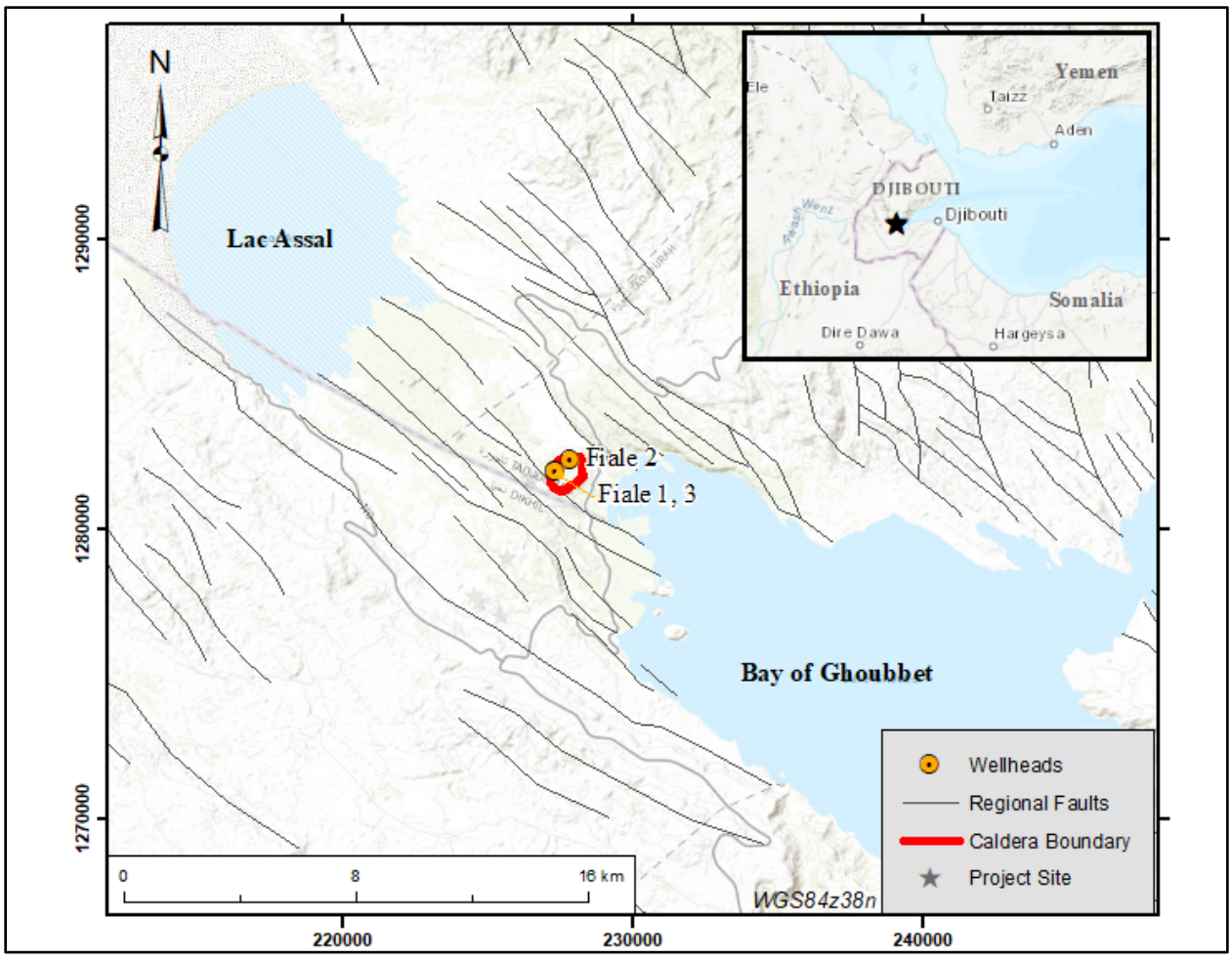

Figure 7: Map showing the location of the Fiale Caldera between the Bay of Ghoubbet and Lac Assal.

A hydrologic connection exists between the two bodies of water in which seawater traverses from the Bay of Ghoubbet to Lac Assal reportedly along faults or fractures along the north side of the rift. This movement of cooler seawater through the subsurface of the Fiale Caldera may have cooled the geothermal reservoir resulting in the discrepancy between temperatures indicated by the alteration minerals and those measured.

Note that in Fiale-1 well, smectite disappeared at 524 m MD and epidote was first noted at ~900 m MD suggesting the well had traversed below the cooler cap and into temperatures of ~250°C. The casing was then set at 1189 m MD. However, the temperature at this point was actually around 70□C. In the following wells, Fiale-2 and Fiale-3, the casing was set below this cold zone, but the alteration mineralogy did not help identify the top of the reservoir during drilling nor support selection of casing depth.

6. Conclusion

Alteration mineralogy can be indicative of current reservoir temperatures and provide a valuable guide for drilling decisions. However, in the geothermal wells completed within the Fiale

Caldera, the temperatures based on alteration mineralogy of the cuttings and measured temperatures are inconsistent. The differences between the temperatures may be related to a recent influx of seawater cooling the rock, rendering the alteration mineralogy relic from a period when the subsurface temperatures were hotter. Due to the unique evolution of geothermal systems, it is clear that in the vicinity of the Fiale Caldera, characterization of the reservoir cannot rely solely on the identification of alteration minerals.

Acknowledgement

The authors would like to thank Électricité de Djibouti for permission to publish the data in this paper.

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