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Geological Mapping to the NW of Mt. Fantale, Main Ethiopian Rift

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ABSTRACT

Remote sensing techniques were used alongside field observation to build and verify a geological map at 1:50,000 scale to the northwest of the Fantale caldera near Metehara, Ethiopia, covering an area approximately 280 km^2. Numerous high-level geological investigations have previously been carried out within the region, predominately by the Geological Survey of Ethiopia. This study presents findings that have corrected significant discrepancies in previous publications, detailing fault structures and lineaments and refining geological boundaries in the most densely faulted region of the Main Ethiopian Rift, with spectral mapping also attempted in the rift. Various basaltic horizons are located within exposed fault scarps, with two main ignimbrites blanketing the area, primarily the distinctive Fantale ignimbrite, a green, blistered and welded ignimbrite; the product of the caldera-forming eruption.

1. INTRODUCTION

Mt. Fantale is a prominent stratovolcano located in the Northern Main Ethiopian Rift (MER) near the town of Metehara and adjacent to Lake Beseka, rising to a maximum elevation of 2,007 m from the surrounding plain. Fantale has an extensive eruptive history as one of the most active volcanoes in the axial part of the MER (Acocella et al., 2002). The Quaternary caldera-forming eruption resulted in the iconic, elongate summit caldera ubiquitous with large Quaternary edifices in this part of the MER. The most recent eruption was to the south of Mt. Fantale in 1820, a fissure eruption of obsidian and basaltic flows (Gibson, 1967).

Cluff Geothermal Limited (CG) were awarded the Fantale Geothermal Exploration Licence Area in July 2015. The Fantale Geothermal Licence Area covers approximately 1260 km^2 and is located within three National Regional States: Amhara, Afar and Oromia.

CG undertook a large-scale surface exploration programme during 2015 and 2016 to establish the existence and size of a commercial geothermal resource suitable for electricity generation associated with the Mt. Fantale edifice. Alongside geological mapping of the main area of interest through remote sensing techniques and field mapping, as detailed in this paper, CG also undertook a 246-station magnetotelluric (MT) study, and fluid sampling and analysis of surface waters during this period.

2. VOLCANO-TECTONIC SETTING

The East African Rift System is the southern arm of the Afar Triple Junction and extends south around 4000 km. The Ethiopian Rift is an active rift between the Ethiopian Plateau to the northwest and the Somali Plateau to the southeast (Gibson and Tazieff, 1970), extending 1,000 km from the Kenyan border to central Afar (Mohr, 1983). The axial part of the rift, to the south of the Afar Triangle, is known as the Main Ethiopian Rift (MER).

The MER is classified into three main sections, the Northern MER, the Central MER and the Southern MER, each has varying volcanic and tectonic characteristics. The onset of volcanism and faulting differs across the MER segments, with diachronous activation of border faults with the northward progression of the rifting process (Agonstini et al., 2002, Boccaletti et al., 1999). Border faults did not activate in the Northern MER until the late Miocene, alongside the onset of syn-rift volcanism; 10-11 Ma (Bonini et al., 2005). A south to north decrease in crustal thickness across the MER is seen in seismic data (Hayward and Ebinger, 996).

Two distinct systems of normal faults characterise the MER; the rift-valley border faults and rift-floor faults (Mohr, 1967). In the Southern and Central MER border faults dominate, while in the Northern MER, a dense set of right-stepping en-echelon normal faults, known as the Wonji-Fault Belt, dominates. The evolution of the MER is controlled by the large-scale, long-term Nubia-Somalia plate kinematics (Agostini et al., 2011).

2.1 Northern Main Ethiopian Rift

The Fantale edifice is located near the southern extent of the Northern MER. The Northern MER is defined as stretching from the Afar depression to the Lake Koka region, south of the city of Adama. (Bonini et al., 2005).

Following an early phase of roughly normal extension orthogonal to the rift trend in the Northern MER, oblique extension has been active since the beginning of the Quaternary (Boccaletti et al., 1997). The onset of oblique extension, due to the re-orientation of the stress field (Boccaletti et al., 1999), and accommodated through the development of the Wonji-Fault Belt, began 1.6 Ma ago (Meyer et al., 1975). The Wonji-Fault Belt, while primarily affecting the rift floor, also overlaps with some segments of the margins. The onset of oblique rifting phase therefore followed an earlier, roughly orthogonal phase of extension. (Boccaletti et al., 1997). This two-stage faulting and rifting history was successfully modelled by Bonini et al. (1997).

The Wonji-Fault Belt is a tecto-volcanic system of right-stepping, en-echelon, dense swarms of normal faults, generally exhibiting relatively small offsets (<100 m). The Wonji-Fault Belt is clearly defined in the Northern MER, obliquely cutting the rift floor. (Agostini et al., 2011). These en-echelon magmatic segments accommodate 80% of the strain across the Northern MER (Ebinger and Casey, 2001) with border faults no longer the focus of extension. Deformation remains concentrated in the border faults in the Central and Southern MER.

Melt-induced seismic anisotropy within the uppermost crust shows magma intrusion occurs throughout the whole lithosphere in the Northern MER and underlies the Wonji-Fault Belt. Magma injection localises and accommodates strain, facilitating continental break-up with only minor crustal stretching (Kier et al., 2005, Kendell et al., 2005).

2.2 Mt. Fantale history

Mt. Fantale is a dormant strato-volcano of Quaternary age which dominates the local landscape. The caldera-forming eruption is dated at 170,000 ka, resulting in an elliptical caldera measuring approximately 2.5 x 4 km and the emplacement of the Fantale Ignimbrite. The Fantale caldera contains a depression of approximately 100 m and is aligned E-W, oblique to the rift axis. The E-W alignment of the Fantale caldera, as well as the Kone and Gedemsa calderas, is thought to be the result of the reactivation of pre-rift E-W aligned fractures during rifting, which also control the development of magma chambers. The alignment of the calderas is the surface expression of this control, opposed to an extensional feature (Acocella et al., 2002).

The other significant feature of the region is Tinish Fantale, a heavily eroded former volcanic centre rising about 100 m above the surrounding plain to the NW of the main Fantale edifice. The greater Fantale area contains a number of cinder cones, volcanism associated with the NNE-SSE trending faults. The fissure eruption of 1820 is the most recent eruption at Fantale, occurring to the south of the main edifice, erupting basaltic and obsidian flows which extend to Lake Beseka.

3. GEOTHERMAL EXPLORATION IN ETHIOPIA

Ethiopia began geothermal exploration in 1969, building an inventory of potential resources and surface manifestations. Approximately 120 localities have been identified as potential heating and circulation systems, with 12 initial areas identified as potential high-enthalpy systems capable of electricity generation (Teklemariam and Kebebe, 2010).

Geothermal activities peaked, arguably to a height not seen since, in the 1980's with exploration drilling activities at Aluto-Langano, and then in the 1990's at Tendaho. A pilot project with a net power potential of 7.3 MW_e becoming operational at Aluto in 1998; current output is significantly less than this.

While Ethiopia is not currently issuing geothermal licences, several active exploration licences have been issued to both public and private entities, including state owned and private international development companies.

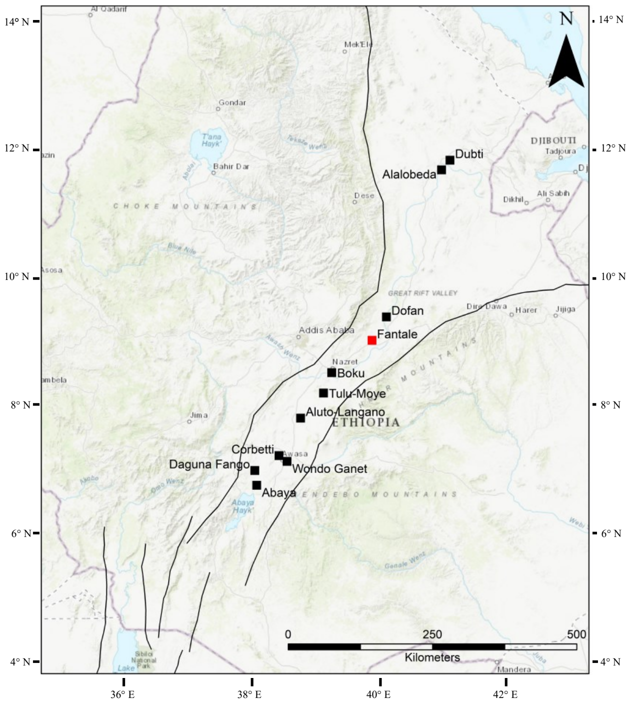

Figure 1. Active exploration/development geothermal licences issued by the Government of Ethiopia. All issued licences are location within the MER. Fantale, the only geothermal exploration licence held by CG in Ethiopia is highlighted. Rift-valley boundary faults are shown.

3.1 Past exploration at Fantale

Geological investigation at Fantale can be dated back to LaCroix's study in 1930. Gibson (1967) published the preliminary detailed geological account of the Fantale area outlining stratigraphy, petrology and structural features alongside a rudimental geological map; covering an area from Lake Beseka to the Fantale caldera. This work built upon the larger scale investigation into the MER by Mohr, amongst others, in the early 1960's.

It was not until geothermal energy investigations began that detailed geological maps were published for the Fantale area. Fantale's inclusion as part of Italy's ELC Electroconsult's reconnaissance study in 1987 kickstarted a period of geothermal exploration resulting in a number of publications containing geological maps from the late 1990's until the 2000's. Multiple iterations of the geology of the Fantale region have been published by the GSE. The GSE has carried out geothermal exploration activities in the form of geological, geochemical and geophysical investigations at Fantale.

The work undertaken by the GSE shows inconsistencies across publications. The three main productions of the geology of Fantale by the GSE were published in 1999, 2003 and 2007. In 1999 and 2007, maps were produced at a regional scale while a detailed 1:50,000 geological map centred on the Fantale caldera was published by Mamo and Gataneh (2003).

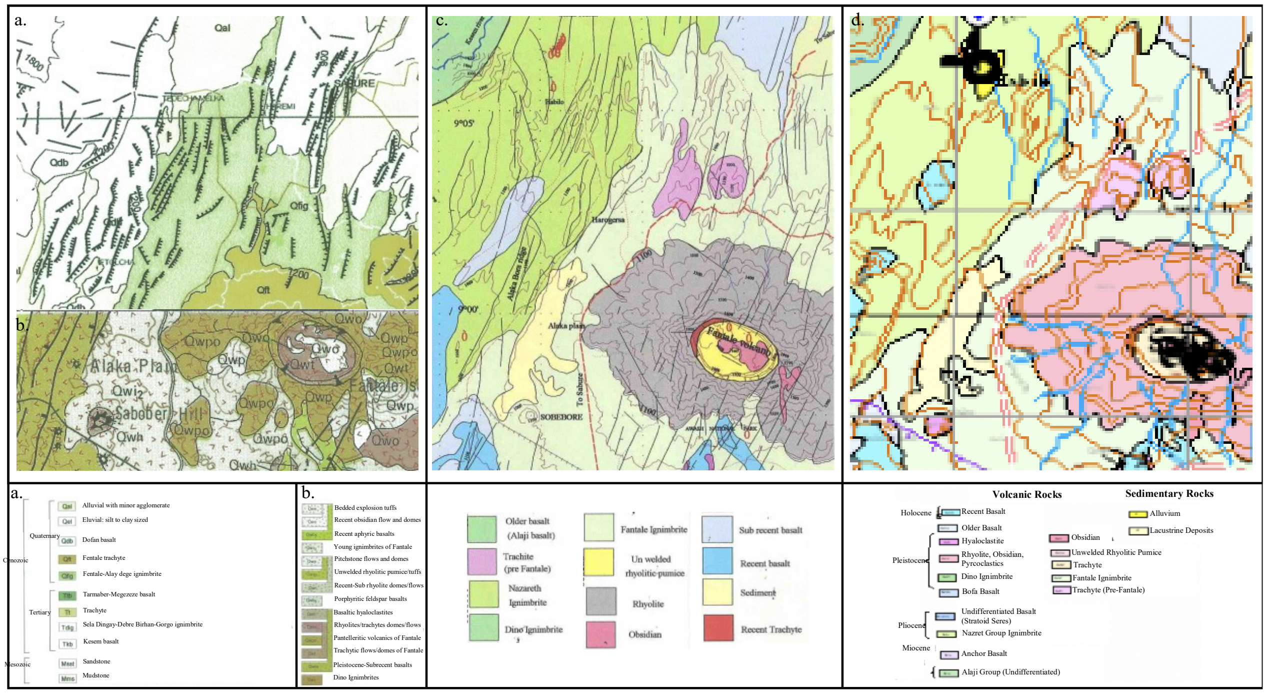

Figure 2. Geological maps showing the focus area of CG's geothermal exploration activities to the NW of the Fantale caldera. From left to right: sheet a) Meshesha et al., 1999, sheet b) Kazmin and Berhe, 1978, c) Mamo and Gatenah, 2003, d) Bekele et al., 2007. Maps manipulated to display at a comparable scale.

Due to the sheet not extending beyond the northern flank of the Fantale caldera, Meshesha et al.'s (1999) publication is supplemented by Kazmin and Berhe's map of Nazret (1978). Both describe the flanks of Mt. Fantale as being composed of Pantelleritic volcanics/trachyte with the Fantale Ignimbrite blanketing the area beyond the flanks of the volcano. On the western and north-western edge of the mapping area, *Sheet a* displays Pleistocene-subrecent basalts and *Sheet b* the Dofan basalt.

Mamo and Gebenah's map (2003) published at a 1:50,000 scale displays structural features of the area in greater detail. Mamo and Gebenah disagree almost entirely with the publication from 1999. While agreeing that the Fantale Ignimbrite surrounds the entirety of the caldera, they describe rhyolite deposits making up the flanks of Mt. Fantale and note an occurrence of trachyte to the north of the caldera, not included within the earlier publication. They describe an occurrence of the Nazareth Ignimbrite in the NW of the mapping area, opposed to the widespread basalts previously described. Mamo and Gatenah identify the occurrence of basaltic outcrops due west of the caldera, within the region of the Nazreth Ignimbrite.

Bekele et al. (2007) published their map at a regional scale. Their mapping of the Fantale area is clearly influenced by the earlier work of Mamo and Gebenah, albeit displayed slightly simplified owing to the scale.

4. GEOLOGICAL MAPPING AT FANTALE

This investigation aimed to create a 1:50,000 structurally detailed and lithologically accurate geological map of the area of interest, reconciling the differences in previously published geological maps of the region.

Remote sensing techniques have been available for satellite geological mapping since the launch of Landsat-1 in 1972. Landsat-8, launched in 2013, collects medium resolution (30-meter spatial resolution) multispectral image data across nine short-wave bands alongside long-wave thermal images.

As Mt. Fantale sits within the most densely fault section of the MER (Figure 3), mapping all fault structures and lineaments in the field would be time-consuming and potentially less effective. Due to the nature of the fault regime in the region coupled with the lack of vegetation, utilising satellite images to reconcile faults offers a particularly time-effective technique to construct a detailed structural map.

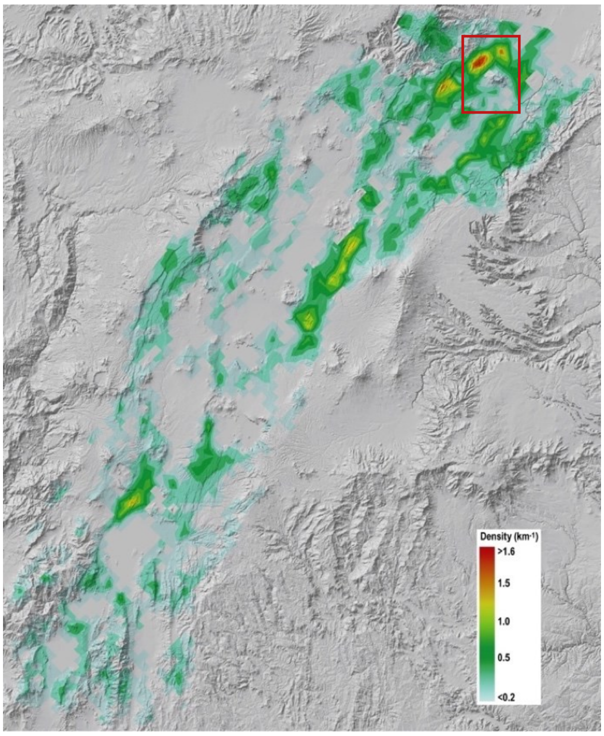

Figure 3. Map of fault density distribution within the axial part of the MER superimposed onto a shaded relief map, with the Fantale Geothermal Licence illustrated. The density has been calculated for 5 km-sided square cells as the ratio between the cumulative length of faults contained in each cell and the area of the cell, over a grid that is oriented nearly parallel to the overall envelope of the fault network. (Agonstini et al., 2010)

Landsat-8 OLI (Operational Land Imager) images were utilised alongside a SRTM DEM (Shuttle Radar Topography Mission digital elevation model) to create a structural map of the area of interest to the NW of the Fantale caldera, covering an area of approximately 280 km^2. This was combined with lithological boundaries from an existing GSE geological map to create a first-pass geological outlook for the region.

Using remote-sensing techniques to identify faults allows quantitative analysis from the resulting database to be undertaken. The alignment of the normal faults within the area of interest was investigated and the resulting rose diagram is shown in Figure 4, revealing a distinct NNE-SSW trend, typical for the Wonji-Fault Belt.

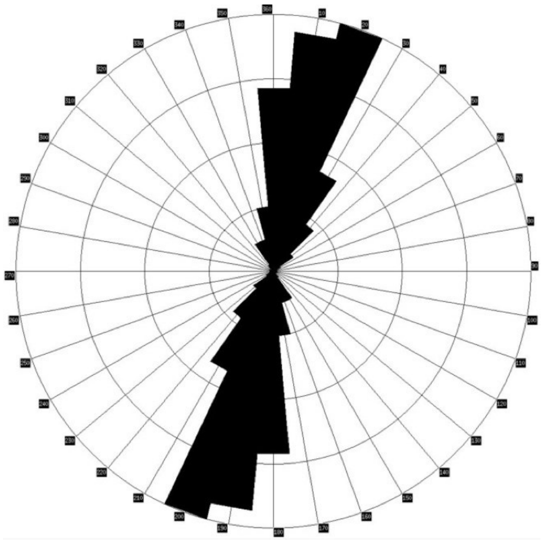

Figure 4. Rose diagram illustrating the strike of normal faults within the mapped area.

4.1 Field-verification

Field geological mapping was undertaken over an area of approximately 30 km^2 stretching from the NW slopes of the Fantale edifice towards the western bounding faults of the MER. A mapping strategy was devised based on previously published GSE works, allowing lithological boundaries and areas of contention between previous publications to be prioritised for field investigation.

The oblique rifting in this part of the MER induces a high sinistral shear gradient, responsible for the occurrence of trans-tensional structures close to the eastern border (Boccaletti et al., 1992). The Habilo spring, the primary manifestation for the geochemical analysis of the Fantale geothermal system, is situated within a rhombic-shaped tensional geological structure, clearly visible from the satellite images. Pull-apart basins are common features of commercial geothermal systems as areas of potentially enhanced secondary permeability. The Habilo basin was considered the primary target for initial exploration activities and the mapping area is roughly centred upon it.

Field verification was undertaken between January and March 2016 as part of the wider, large-scale geothermal energy surface exploration phase with over 30 localities visited and three main lithologies identified and classified.

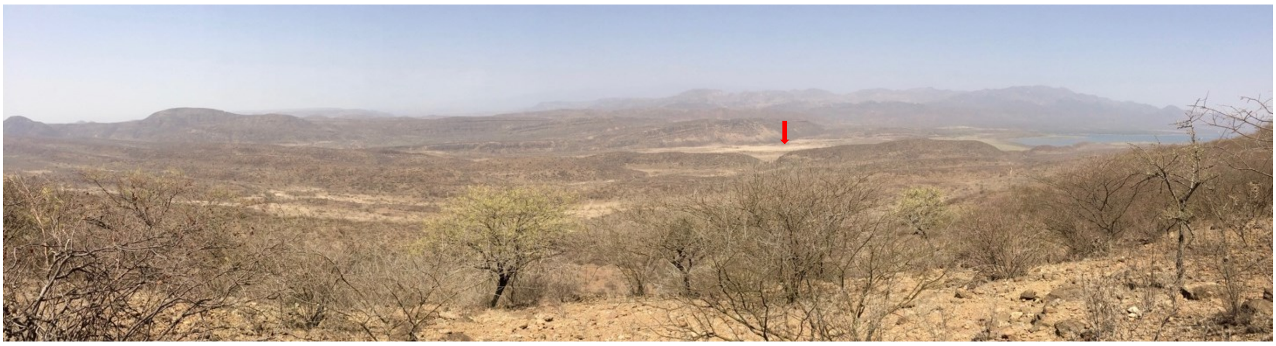

Figure 5. Looking north-west across the field mapping area with the Habilo spring labelled.

Stratigraphy sequences within the region have been named and referenced differently by past authors. While correlations of the named stratigraphy have been attempted, the most comprehensive was compiled by JICA (2015). The correlations and terminology outlined by JICA have been adopted by this study.

4.1.1 Fantale Ignimbrite

The Fantale Ignimbrite is found within the mapping area on the plains to the east and north-east of the Fantale caldera. The most characteristic trait of the Fantale Ignimbrite is its vivid green colour. It is strongly welded throughout its thickness and contains elongate, largely pumice, fiamme distributed throughout. It also contains lithic inclusions, typically no larger than 3 cm.

While the Fantale Ignimbrite is generally moderately weathered, in places the weathering is extensive, resulting in the loss of its distinctive green colouration, weathering to a loose, crumbly, featureless, brown unit.

The Fantale Ignimbrite is the result of the caldera-forming eruption, and while it can reach a thickness of 30 m on the plains, it is significantly thinner up the flanks of the volcano and is the most extensively studied unit within the mapped area. The flow is welded in its entirety and it is observed that no pumice-fall deposit is present either above or below the welded flow. Elongate fiamme are present throughout the unit, even when the unit is only 30cm thick. Vesicles within these fiamme have been found to be spherical and undeformed and therefore the fiamme are not the result of collapsed pumices under the lithostatic load of the overlying deposit. It is suggested that the Fantale Ignimbrite is the result of an exceptionally high temperature eruption (Gibson, 1970).

Despite being located outside of the mapping area for this study, when discussing the Fantale Ignimbrite one should mention the unusual ignimbrite blisters which are widespread on the surface on the flow but mainly distributed to the south-west and south of the caldera. The blisters are typically 30-40 m in length but can reach lengths of up to 100 m. They are particularly visible from the track leading to the village of Hara Qarsa, rising prominently against the flat surrounding plain. The blisters are thought to be the product of the emplacement of the ignimbrite across a shallow lake or swampy ground with sudden vaporization of the water causing steam to bulge and blister the hot and plastic surficial deposit (Bekele et al., 2007).

4.1.2 Nazret Group

The Nazret Group outcrops on the NW of the mapped area, beyond the extent of the Fantale Ignimbrite and towards the western rift shoulder. In this region, the unit is predominately made up of a highly weathered ignimbrite series. The ignimbrite is generally grey in colour but can be observed showing grey-green and grey-blue colourations.

Similar to the Fantale Ignimbrite, the unit is strongly welded. It contains lithic fragments, predominately of pumice but also of tuff and basalt. Unlike the Fantale Ignimbrite, the Nazret Group shows variations, even across the limited area investigated. This heterogeneity is best illustrated on the scarp adjacent to the main spring within the Habilo basin. While the base of the exposed unit is highly weathered and contains large voids, the central section contains striking, long fiamme of up to 10 cm in length (Figure 5). The top of the exposed unit, however, contains neither fiamme nor lithic clasts. It is difficult to classify the differences across the exposed Nazret Group rocks as either heterogeneity within a single flow or compositionally different flows, predominately due to the degree of weathering. Further lab-based investigation would be required.

Figure 6. Fiamme present within an ignimbrite flow of the Nazret group, adjacent to the Habilo Springs.

The lower Nazret Group has a large age range, with the lower series being dated up to 9.5 Ma (Kuntz et al., 1975) while the upper Nazret series is around 3.5 Ma. While the rocks within the Fantale region have not been dated directly, they are expected to form part of the Upper Nazret series. The Nazret Group can reach thicknesses of 250 m within the rift, and where present on the rift-shoulders, its thickness is significantly reduced (Kazmin and Berhe, 1978).

4.1.3 Recent Basalts

Small outcrops of aphanitic basalt can be observed within the western and north-western section of the mapping area. The basaltic horizons are primarily located at the top of fault scarps and localised in nature. References to the basaltic horizons are largely undiscussed within the literature and therefore it is difficult to correlate the rocks to a pre-described unit. While the basalts could form part of the Stratoid Series (Bekele et al., 2007), for the purpose of this study they are simply defined as 'Basalt', pending further investigation.

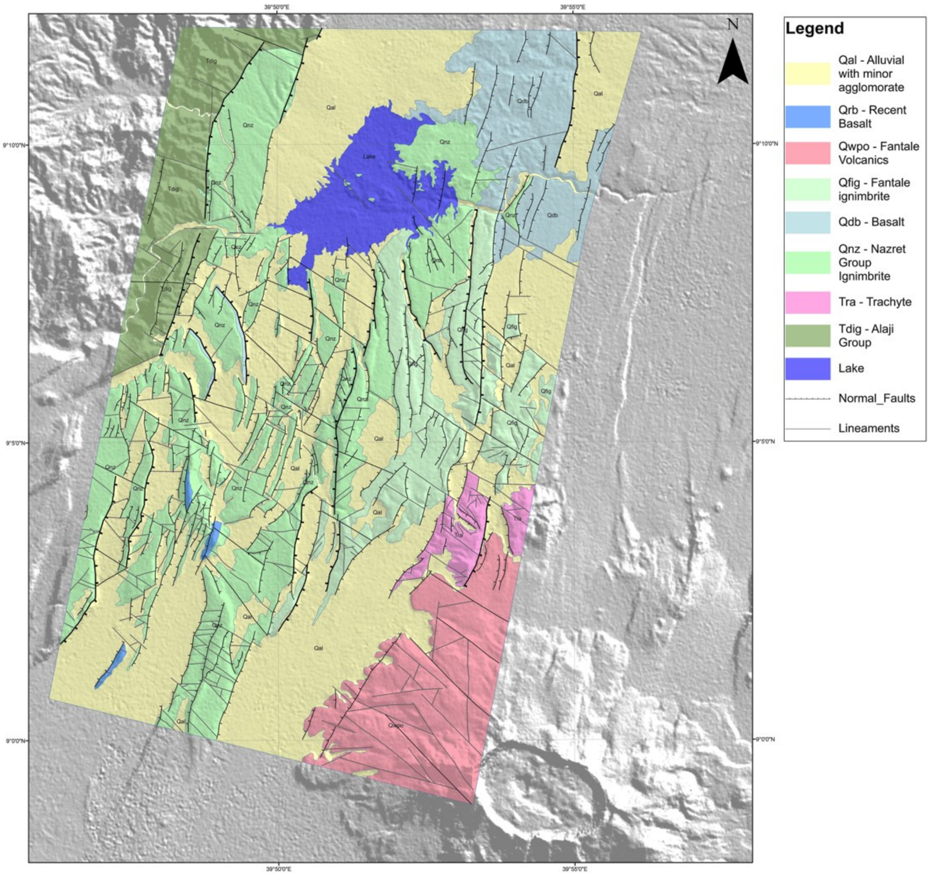

Figure 7. Geological map, detailing structural features and lithologies in the NW region of Mt. Fantale. Geological features overlying a shaded relief map.

5. SPECTRAL MAPPING AT BUTAJIRA, ETHIOPIA

The use of remote sensing techniques alongside field-verified lithological identifications was a successful and time-efficient method for producing a detailed geological map of the area of interest at Fantale. ASTER TIR (thermal infrared radiometer) multi-spectral bands have been successfully utilised to differentiate lava flows in the Erta Ale range in the Afar region of the Northern Ethiopian Rift Valley, as the varied SiO_2 content of surface-exposed rocks influences the thermal emission spectrum (Watanbe and Matsuo, 2003). Using spectral mapping as a means of lithological identification would allow both structural and lithological information to be gained without the requirement for field verification. Prior to field verification at Fantale, the spectral mapping technique was attempted by CG at another potential geothermal resource: Butajira, located within the Central MER.

The spectral mapping exercise hoped to aid the structural mapping by extending the study to differentiate lithologies and identify manifestation through analysing hydro-thermal alteration products. Thermal infrared mapping was also deployed to identify hot springs. ASTER day-night images used the SWIR bands of the ASTER data to investigate variations in occurrences of Montmorillonite, Kaolinite, Illite, Calcite, Carbonate, Iron oxide and Argillic alteration.

At Butajira the majority of the area's spectral signature is controlled by clay-rich lacustrine sediments. While mineralisation can be identified along some fault slopes, it is not clear if these represent springs or mineralised fault zones. The work allowed the identification of thermal manifestations in a few locations where both thermal and spectral signatures are present, showing a clear link exists between the two. It was not possible to undertake lithological identification from the spectral mapping; this is partially due to the high degree of surface weathering altering the spectral signatures and making differentiating lithologies difficult. Deriving spectra from hand-specimens or in the field using a PIMA (Portable Infrared Mineral Analyser) has the potential to improve the remote sensing technique for lithological identification in this region.

6. CONCLUSION

Remote sensing techniques, specifically open data from Landsat-8, present a cost and time effective way of building a detailed structural base map for a region, particularly in remote areas where it may be difficult to operate. The Fantale Geothermal Licence is situated in the region with the highest density of faults within the MER and the use of satellite data and remote sensing techniques allowed the dense swarm of faults and lineaments associated with the Wonji-Fault Belt and the rift margins of the MER to be mapped in detail.

Previous geological investigations in the region published by the GSE contains discrepancies. The field verification work allowed these to be corrected and lithological boundaries to be placed accurately, in particularly between the Fantale Ignimbrite and the older Nazret Group. Basaltic horizons were identified to the west of Fantale, not previously described within the literature. The effects of weathering within the region makes geological investigation of the ignimbrites difficult in a field environment. This is particularly relevant within the older Nazret Group.

Spectral analysis was not immediately successful in delineating lithologies when attempted in the Butajira region. The project shows the importance of integrating field and remote sensing techniques and that best practise involves iterative processes that should be used to constantly improve exploration models and understanding.

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