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# Petrophysical variations within the basaltic lava flows from Tural-Rajawadi hot springs, Western India and their bearing on the viability of low-enthalpy geothermal systems

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**Abstract.** The Tural-Rajawadi hot springs (Temp. 30-62 °C) are a part of the West Coast Geothermal Province of India, located at the foothills of the Western Ghats in Maharashtra state. The hot springs manifest as several small pools/puddles along lineaments within the valley that exposes five (5) surficial lava flows belonging to the Cretaceous Deccan Traps. In addition, six (6) distinct lava flows were identified based on their internal structure, textural variations, vesiculation and presence of glassy rinds in the 203m deep exploratory borehole drilled at Rajawadi. These lavas are of pahoehoe sheet flow and rubbly pahoehoe morphologies. Temperature of water increased from 51 at the top to 62 °C at the bottom. XRD studies of vesicle and joint fillings within the lava flows reveal peculiar assemblage of calcite, nontronite, clinopitohite, stilbite, apophyllite, cristobalite, etc. indicating mineralisation related to circulating hot geothermal fluids. The detailed petrophysical properties like textural diversity, crystal size distribution, specific gravity (2.766 to 2.999), resistivity (295.5 to 1790Ωm at 50Hz) and thermal conductivity were measured and their variations within two (2) thick subsurface lava flows is presented. These variations can be attributed to the crystallisation, cooling history, post emplacement hydrothermal alteration and mineralisation the lava flows have undergone. Understanding these variations is essential for assessing viability and commercial feasibility in using and exploiting low-enthalpy geothermal systems.

## 1. Introduction

Geothermal energy is the energy contained within the earth's interior that manifests in various forms, ranging from a higher geothermal gradient than expected, to hot springs, fumaroles and even volcanoes. Geothermal energy is being used as an alternative energy source in many parts of the world due to it being clean and having a low maintenance cost.

Several geothermal fields have been identified in India, with some having a high potential and others having sub economic value. Over 300 known hot springs have been identified in India, caused by the presence of various tectonic elements such as shear zones and fault planes. The various geothermal provinces outlined by GSI in 1991 are the Himalayan Geothermal Province, Naga-Lushai Province, Andaman-Nicobar Island Province, West Coast Province, Cambay Graben Province, Aravalli Province, Son-Narmada-Tapi Province, Godavari and Mahanadi Province and the South Indian Cratonic Province



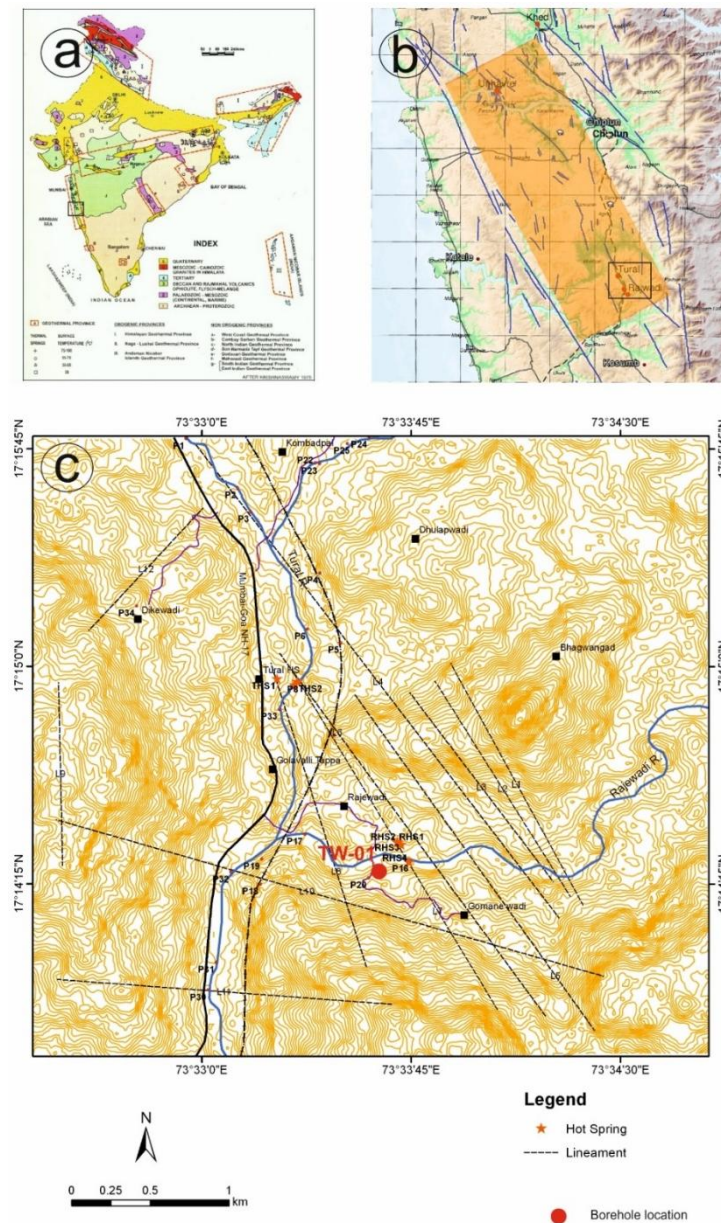
Earliest attempt to list the thermal springs in India was made by Schlagintweit in 1962. Subsequently, Oldham documented some of the occurrences by the turn of the Nineteenth Century. Preliminary reconnaissance surveys related to location, temperatures and medicinal qualities of hot springs were undertaken by several workers like Gosh [13], Deb [8], Chandrashekaram [6], [7] etc. In the late '60's, Government of India constituted a "Hot Spring Committee" that lead to a systematic geothermal studies and exploration in India.

Over the decades, a lot of valuable information on geothermal areas and hot springs has been generated. These have been used both for academic and exploratory purposes. In 1991, the GSI compiled and published the 'Geothermal Atlas of India'. The voluminous data has been used to prepare the Geothermal Map of India and define the Geothermal Provinces of India (Fig. 1a). Since recent years, private entrepreneurs have developed expertise and keen interest in using low enthalpy geothermal systems for exploration and development. Thermax India Pvt. Ltd. in their exploration for geothermal resources had drilled cores in the Tural-Rajwadi area [10]. One such set of cores was made available for geophysical studies to us.

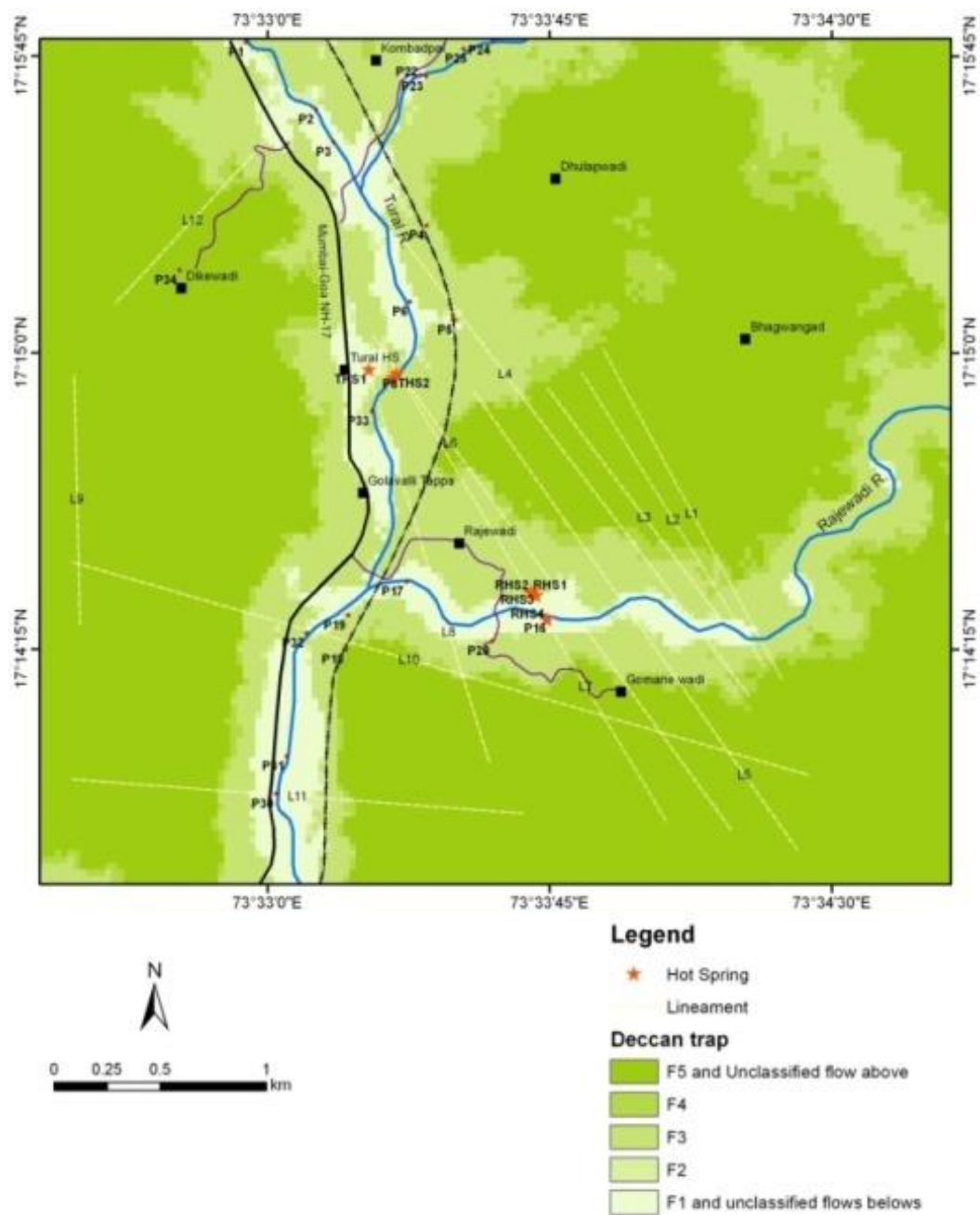
In this paper, we present data generated on the cores from the Tural-Rajwadi area (Fig. 1b,c). Detailed core logging of select samples of two out of six flows (F3 and F5) was carried out, and they were classified into lava types accordingly. Detailed petrophysical studies (specific gravity, electrical resistivity, thermal conductivity and textural analyses) of 46 samples from the two aforementioned flows were undertaken, and attempts were made to correlate variations of physical properties with that of modal proportions of the minerals with an aim to generate baseline data for further geothermal modelling of the low enthalpy system.

## 2. Study area

The present study area is located within the west coast geothermal field (Fig 1b), which consists of 60 thermal springs clustered around 18 localities and extending for a distance of 300 km from Koknere in the north to Rajapur in the south [14]. The springs are controlled by dykes, shear zones, fractures and the NNW-SSE trending lineaments. The general topography of the Tural-Rajwadi area consisted of hills, valleys and plateaus, although a major part of the study area was a valley through which the Tural stream flows (Fig 1c). Hilly terrain is seen in the NE (around Dhulapwadi), East (Bhagwangad) and SE (Gomaewadi). Several fracture lineaments are seen in the area (Fig. 1c). The basaltic lava flows, belonging to the Deccan Traps are predominantly exposed in the area. A total of 5 lava flows can be identified in the area on the surface (Fig. 2). Three lava flows are exposed in the valley. The lava flows are of the simple type with rubbly tops [9], [12], [19], [21]). All the flows identified in the study area belong to the Poladpur Formation [2]. Five flows were successfully identified on the surface, with the first four having thicknesses of 20m, 1.9m, 29.9m and 6.9m respectively. The top of the fifth flow could not be mapped due to thick vegetation and deep weathering. Six lava flows were identified in the subsurface (Table 1) based on their internal structure, textural variations, vesiculation and presence of glassy rinds (Fig. 3). Of these, 3 lava flows (F2, F4, F6) show pahoehoe affinity [4], [5], [18], [20] and 2 lava flows (F3 and F5) show rubbly pahoehoe affinity [11]. XRD studies of vesicle and joint fillings within the lava flows reveal peculiar assemblage of calcite, nontronite, clinopitilite, stilbite, apophyllite, cristobalite, etc. indicating mineralisation related to circulating hot geothermal fluids [15].



**Figure 1** Maps depicting a) geothermal fields of India (from GSI) b) part of the West Coast Geothermal field along the Western Ghats c) the Tural-Rajwadi hot spring area showing the location of the exploratory bore well (TW 01)

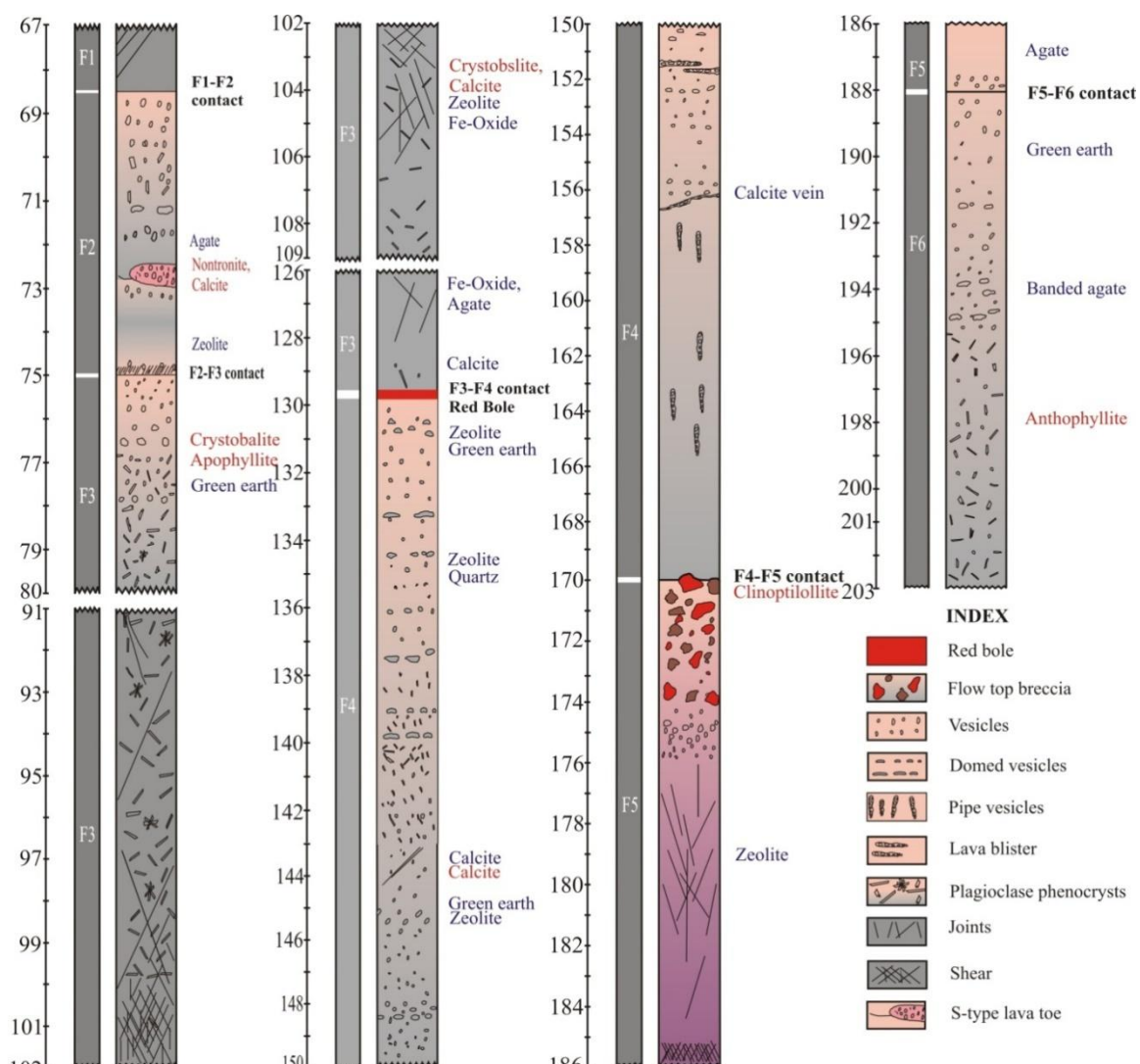


**Figure 2.**Geology of the Tural-Rajwadi area showing the distribution of lava flows and major lineaments (after [10])



### 3. Methodology

Two intact lava flows (F3 and F5) from the Tural-Rajawadi borehole were chosen for detailed petrophysical characterisation. Samples within the cores were chosen based on their textural variations and freshness. Thirty-one (31) samples were chosen from lava flow F3 and fifteen (15) from lava flow F5. Specific gravity, electrical resistivity and thermal conductivity of the samples were measured. The modal proportions of the samples were also measured from the thin sections prepared. Specific gravity was measured directly by measuring weight of samples in water and their weight in air. Electrical resistivity was measured using AC power source of 50Hz, using Ohm's Law. Thermal conductivity was measured using a steady state method, similar to what was prescribed by Birch (1950). Modal proportions were measured using digital photographs, with samples being analysed digitally using Fiji [17].

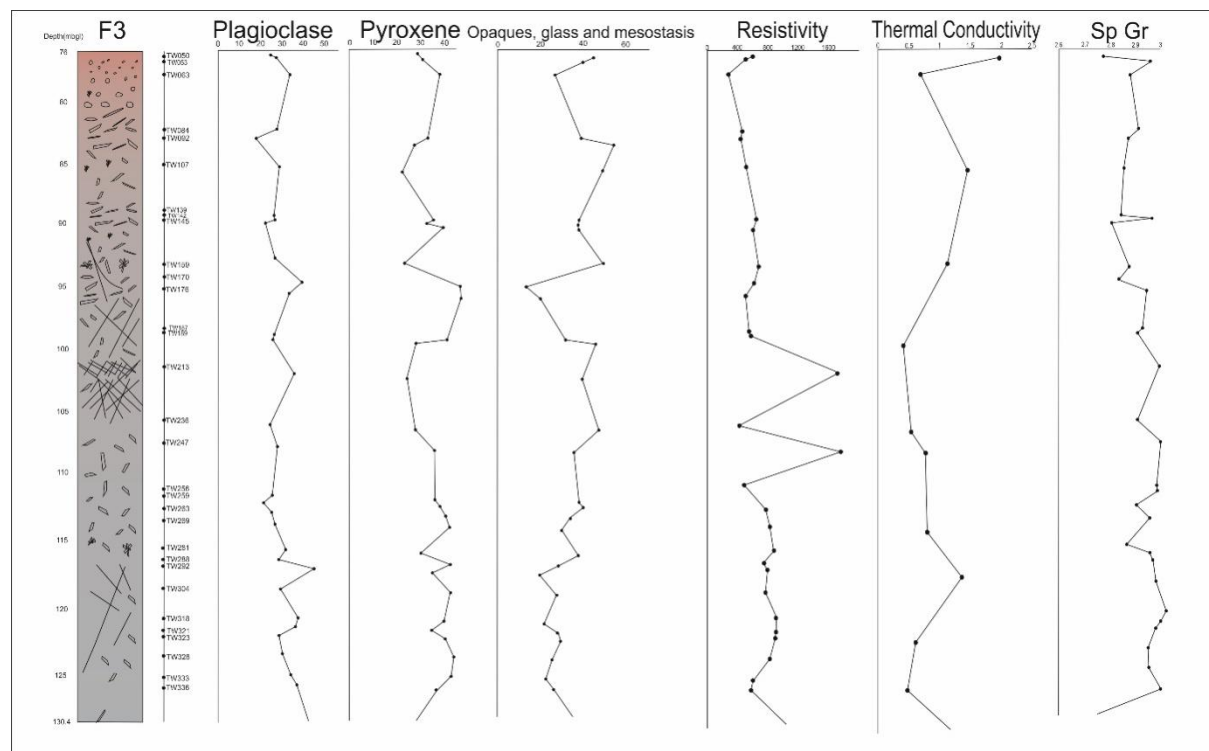


#### 4. Results

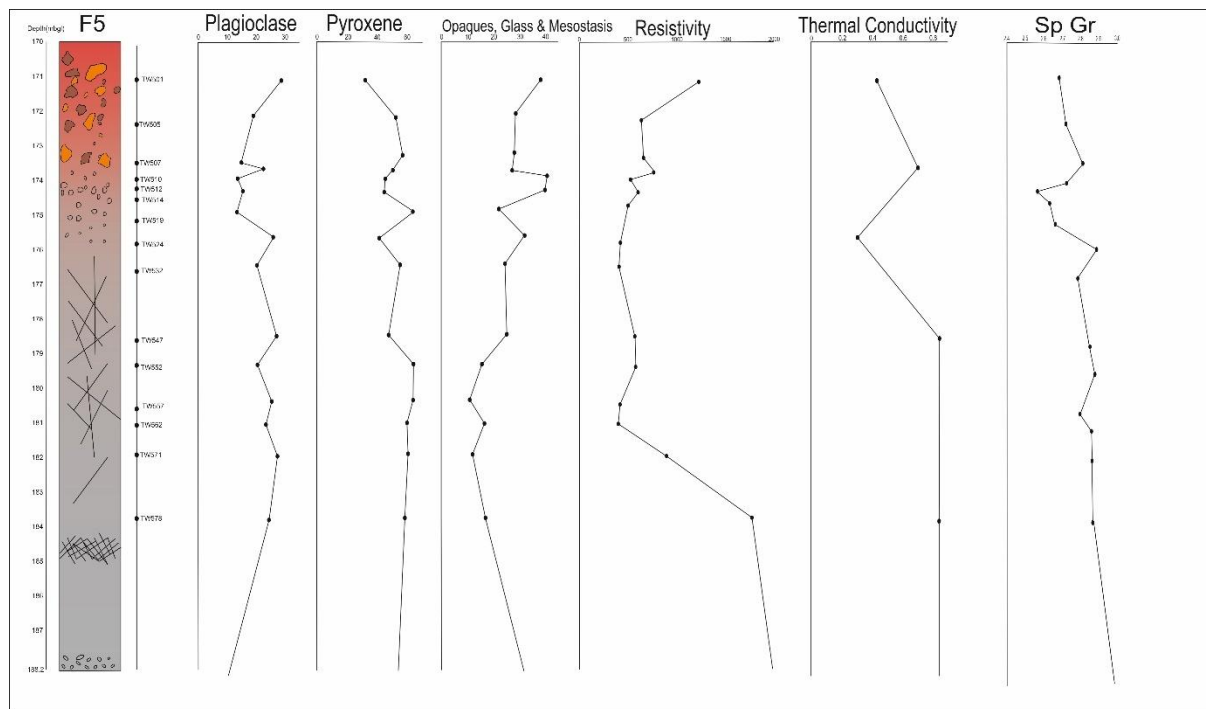
The results of the specific gravity, electrical resistivity and thermal conductivity (Table 2), along with the modal mineralogy (Table 3) of the measured samples are presented in figures 5,6. In general, it is seen that the specific gravity of the core of both lava flows is higher than their respective crust. Over all, the specific gravity increases with opaque and pyroxene contents and decreases with plagioclase, glass and mesostasis contents.

Except for two anomalous results in F3 viz. TW213 and TW247, the electrical resistivity for both flows shows an approximately parabolic curve, with high resistivities in the crust and the base of the lava flows. The reason for the anomalous resistivities is probably due to the presence of microvesicles in the sample. The distribution and type of vesicles and their interconnections within the pahoehoe crust [1] could influence thermal conductivity. Secondary minerals like presence of calcite and other minerals indentified in the XRD studies may also be responsible for high resistivity. Electrical resistivity increases with plagioclase and glass, opaque and mesostasis contents, and decreases with pyroxene contents. Electrical resistivity shows opposite trends in the crust and core for glass, mesostasis and opaque contents for both flows (though the crust of F3 is sampled only twice).

Thermal conductivity shows opposite trends in the crust and core for F5. These opposite trends are due to the presence of a higher number of vesicles in the crust, whose presence affects thermal conductivity to a greater extent than modal contents [16].



**Figure 4.** Modal contents and geophysical property variations within a flow F3 with depth



**Figure 5.** Modal contents and geophysical property variations within a flow F5 with depth

## 5. Conclusions

This study provides preliminary insights into the wide variations in the modal as well as petrophysical properties in the interior of basaltic lava flows from continental flood basalt (CFB) province. These variations were thought to be primarily mineralogical in nature. However, our studies demonstrate that the nature and secondary mineralogy within the vesicles, presence of microfractures and degree of weathering/alteration could be additional factors controlling the petrophysical properties of basalt. These preliminary results provide interesting insights into the emplacement and cooling histories of thick lava flows in CFBs and any attempt to simplify and use average petrophysical values during geothermal simulation and modelling of low-enthalpy geothermal systems would result in grossly erroneous interpretations.

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**Appendix:****Table A1** Subsurface lava flows identified after drilling

Flow No.	Lava Type	Total Thickness(m)
F1	Not identified	-
F2	Compound Pahoehoe	6.5
F3	Rubbly pahoehoe	54.4
F4	Pahoehoe sheet	35.6
F5	Rubbly pahoehoe	18.2
F6	Pahoehoe sheet	~14.5

**Table A2** Physical properties measured in the present study

Sample	Depth (in mbgl)	Specific gravity	Resistivity (in $\Omega$ m)	Thermal Conductivity (in W/mK)
<b>Lava flow F3</b>				
TW050	76.6	2.766	599.136	1.99
TW053	76.92	2.956	526.6645	--
TW063	78.09	2.88	295.5744	0.69
TW084	82.56	2.913	477.5154	--
TW092	83.35	2.868	448.0776	--
TW107	85.45	2.851	528.879	1.45
TW139	89.29	2.848	670.1904	--
TW142	89.5	2.965	--	--
TW145	89.84	2.806	613.8544	--
TW159	92.61	2.875	689.6144	1.14
TW170	94.45	2.829	613.2607	--
TW176	95.38	2.939	511.7952	--
TW187	98.66	2.918	567.9701	--
TW189	98.93	2.903	622.431	0.41
TW213	101.65	2.993	1724.312	--
TW236	105.71	2.906	393.4015	0.54
TW247	107.36	2.996	1432.824	0.78
TW256	111.19	2.966	512.5844	--
TW259	111.69	2.966	--	--
TW263	112.5	2.89	775.8049	--
TW269	113.43	2.938	821.5758	0.81
TW281	115.46	2.852	853.6356	--
TW288	116.28	2.936	727.8945	--
TW292	116.94	2.946	818.3264	1.36
TW304	118.5	2.961	778.9435	--
TW318	120.79	2.999	882.4522	--

TW321	121.53	2.982	894.1256	--
TW323	122.12	2.957	843.8394	0.63
TW328	123.58	2.933	805.4444	--
TW333	125.11	2.933	603.2734	0.49
TW336	126	2.983	584.8056	--
<b>Lava flow F5</b>				
TW501	171.53	2.679	1226.245	0.43
TW505	172.59	2.719	651.9848	--
TW507	173.76	2.809	674.4139	--
TW510	174.19	2.722	778.8165	0.70
TW512	174.48	2.535	516.3466	--
TW514	174.87	2.634	583.3380	--
TW519	175.49	2.654	511.7478	--
TW524	176.26	2.829	433.4428	0.30
TW532	177.12	2.783	422.3316	--
TW547	179.28	2.844	566.1900	0.84
TW552	180.15	2.874	566.6185	--
TW557	181.24	2.788	437.6823	--
TW562	181.96	2.847	420.1389	--
TW571	182.9	2.854	911.1821	--
TW578	184.86	2.853	1790.713	0.84

**Table 3:** Modal analysis (%) data generated during present study

Sample	Depth (in mbgl)	Plagioclase	Pyroxene	Glass, opaques and mesostasis
<b>Lava Flow F3</b>				
TW050	76.6	25.02	29.98	44.99
TW053	76.92	27.50	32.33	40.16
TW063	78.09	34.20	38.06	27.75
TW084	82.56	27.77	33.26	39.00
TW092	83.35	17.96	27.46	54.58
TW107	85.45	28.72	22.18	49.10
TW139	89.29	26.27	35.44	38.29
TW142	89.5	26.55	33.20	37.84
TW145	89.84	22.50	39.86	37.63
TW159	92.61	26.92	23.61	49.46
TW170	94.45	39.65	46.94	13.41
TW176	95.38	33.54	47.29	20.19
TW187	98.66	26.74	41.27	31.98
TW189	98.93	26.00	28.00	46.00
TW213	101.65	35.97	24.44	39.59
TW236	105.71	24.65	27.74	47.62
TW247	107.36	27.97	36.19	35.83

TW256	111.19	25.68	36.36	37.96
TW259	111.69	21.90	38.43	39.67
TW263	112.5	25.31	40.63	34.07
TW269	113.43	27.10	42.57	30.34
TW281	115.46	32.08	30.32	37.61
TW288	116.28	28.70	42.86	28.42
TW292	116.94	45.22	35.22	19.57
TW304	118.5	29.76	42.66	27.58
TW318	120.79	38.05	40.06	21.89
TW321	121.53	36.29	35.19	28.52
TW323	122.12	28.98	40.63	29.76
TW328	123.58	30.38	44.01	25.55
TW333	125.11	34.15	43.10	22.75
TW336	126	37.28	36.63	26.08
<b>Lava flow F5</b>				
TW501	171.53	28.79	32.95	38.26
TW505	172.59	18.94	52.46	28.60
TW507	173.76	14.99	56.86	28.14
TW510	174.19	22.45	50.39	27.16
TW512	174.48	13.67	45.48	40.85
TW514	174.87	15.41	44.51	40.08
TW519	175.49	13.36	64.45	22.19
TW524	176.26	26.23	41.80	31.97
TW532	177.12	20.30	55.17	24.53
TW547	179.28	27.01	47.87	25.12
TW552	180.15	20.45	64.14	15.42
TW557	181.24	25.34	63.82	10.84
TW562	181.96	23.39	60.11	16.49
TW571	182.9	27.49	60.66	11.85
TW578	184.86	24.61	58.68	16.71

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