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Temperature-dependent dielectric behavior of basaltic rocks from Deccan traps, Maharashtra

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Abstract
Basast basaltic rocks of Deccan Traps, Maharashtra, where extensive volcanic cover of basaltic characteristics controls the propagation of electromagnetic (EM) waves, which are of great significance in the field of near surface geophysics (e.g., resistivity/EM sounding and, ground-penetrating radar, GPR, Microwaves) / thermal processing. In western India, Deccan basalts range over very wide variations in the range of flow facies (massive, vesicular/amygdaloidal units, intertrappean/red bole horizons) and weathering states, and corresponding differences in the bulk physical properties, which can be transformed into EM heterogeneity at field scale (Patro *et al*., 2005; Ray *et al*., 2021) [1, 5]. Against this background, the present study focuses on temperature-dependent dielectric behaviour of representative samples of Deccan basalt from several localities (Western Ghats - Mahabaleshwar, Koyna - Warna, Pune Plateau, and Nashik Plateau) by broadband dielectric spectroscopy over a low-frequency - RF window (1 kHz - 1 MHz) in controlled heating condition (25 - 375 degC). The research calculates actual permittivity (EPrim) and dielectric loss (Eex removed) micro-EST: Create true values of permittivity (Además, los terminales requeridos para mujear Kontakt conflict:Taborschaltung-Etherertet formula parametrizacion mujlerlich dura perder variaciones Europeojede empedidos.« - Patriarch ('EtaEta), Eles eliminan activaciones 소리가 directos (ABB).

Across the temperature range tested, the value of e' increases systematically as a function of increasing temperature, which is in agreement with improved dipolar/space-charge polarization and the inclusion of conductive components in the denominator of the complex permittivity as a result of increasing thermal energy. At the same timeTan d increases strongly at high temperatures with maximum increases usually seen at low frequencies where interfacial/space-charge polarization and conduction losses are most prominent. Such a frequency-dependent dispersion is in line with well-established models of Maxwell-Wagner-type interfacial polarization and overlapping relaxation mechanisms which are predominant in the kHz-MHz electrical response of heterogeneous porous geomaterials (Loewer *et al*., 2017; Tabbagh *et al*., 2024) [66, 67].

Keywords: Deccan traps, basalt, dielectric constant, loss tangent, temperature dependence, ac conductivity, Arrhenius activation energy, Maharashtra

1. Introduction
Dielectric properties of rocks - particularly the real part of permittivity (E'): The real part of permittivity is the simplest electric property to measure - commonly called "permittivity" or simply "E" (or "permittivity gamma" - this is a deliberate confusion with the electrical resistivity "rho" - which is the reciprocal of electrical resistivity, e.g., "permittivity gamma").Dielectric properties of rocks - particularly the real part of permittivity (E') and the dielectric loss (E" or tandelta) are fundamental controls on how electromagnetic (EM) waves propagate and how energy is In practical terms, the EM phase velocity (and thus travel time and apparent depth to the radar) is controlled by epr and the attenuation and conversion of EM energy into heat in the presence of alternating fields is controlled by epr/eingenschiersonder{Backslash} correlations and the influence on reflection strength of lithologic boundaries, penetration depth, and efficiency of microwave/thermal weakening/processing of rock materials. In basaltic terrains (e.g. Deccan Traps) the value of these dielectric controls are (a) performance of shallow EM imaging, ground penetrating radar (GPR) resonance features, which (b) Interaction of resistivity in terms of EM Pays fitting in layered trap sequences, and (c) energy absorption under microwave irradiation mechanisms of loss and conductivity play a decisive role to determine magnitude of heating rates and spatial uniformity /. Due to the fact that volcanic rocks are often permeated with

Vesicles/amygdales, oxide phases and interflow heterogeneities the dielectric response usually shows a measurable dispersion over frequency bands, and loss may be enhanced with temperature due to increases in charge mobility and conduction contributions to the loss Foundational laboratory measurements were used to obtain baseline dielectric behavior for basalts for large frequency ranges. Classic experimental measurements of dielectric constant and loss tangent of basalt were made from VLT: 100 Hz frequency range to 10s, up to 10 MHz showing sensitivity of the dielectric properties of basalt to composition and exhibiting losses are non-negligibly seen in the low frequency to RF window of frequency for geophysical sensing and industrial EM fields (Hansen *et al*, 1973) [9]. Subsequent research of the deployment have been identified volcanic rock see: microstructure can exercising a first order of the control Dielectric constant of the connected porosity dry successive volcanic rocks supporting come the meaning that radar velocity (or e") variations can be interpreted in terms of porosity variation when mineralogy been constrained reasonable (Rust *et al*, 1999) [10]. Importantly, basalt suites may also exhibit greater variance in epsilon prime values as compared to volcanic rocks that are more uniform in composition, and the reason for this presumably lies in the difference in Fe-Ti oxide modes and associated conductive/polarizable phases (Rust *et al*., 1999) [10]. Temperature adds a new dimension to this picture: Even in nominally "dry" rocks, dielectric response may vary with a change of thermal state due to the contribution of thermally activated conduction and interfacial polarization processes with an increased contribution at higher temperatures, which can lead to an increase of effective loss and likely modify dispersion behavior in kHz-MHz frequency bands (Rust *et al*., 1999) [10].

1.1 Problem Statement

Despite the great geophysical and engineering significance of Deccan Trap basalts in Maharashtra, published temperature-dependent dielectric data sets reported in a consistent, frequency resolved (kHz - MHz) way are poor in the open literature. Much of the existing electrical characterization of the Deccan Volcanic Province focuses on resistivity and magnetotelluric (MT) imaging on a regional scale, which is extremely useful for identifying lithospheric conductivity structure and trap thickness, but does not normally include determination of the laboratory dielectric parameters (ie, tan) that are essential to the modeling of high-frequency electromagnetic (EM) wave propagation, attenuation, and impedance contrasts in basaltic terrains (Patro *et al*., 2005; Patro *et al*., 2009; Patro & Sarma, 2007) [1, 4, 2]. This gap is significant, because dielectric properties determine the velocity and loss of EM waves at the frequencies pertinent to the application of near-surface EM methods, as well as applications in radar type techniques while the dielectric loss also determines the absorption of energy caused by the microwave-rock interactions employed in other newer rock processing and heating studies (Hansen *et al*., 1973; Hartlieb *et al*., 2010) [9, 29]. In addition, Deccan basalts exhibit large petrophysical heterogeneity within this flow units and location which implies that dielectric response is unlikely to be uniform and cannot be reliably inferred from the resistivity structure over a region alone (Prasanna Lakshmi *et al*., 2014; Ray *et al*., 2021) [6, 5]. Therefore, it is necessary to produce similar, frequency-resolved dielectric datasets as a function of temperature for applied modeling as well as site-specific interpretation.

1.2 Objectives

1. Measure and model basalt dielectric properties (e', tan delta, e" andsigma ac) against temperature for different representing Deccan localities in Maharashtra.
2. Quantify the frequency dispersion (1KHz-1MHz) at each temperature step and find situations where the conduction losses are dominant.
3. Estimate Thermal activation behavior of conductivity using Arrhenius analysis and vary between sites.
4. Develop predictive statistical relationships between values of epsilon prime and changes in temperature, frequency, and porosity (as a proxy of microstructure).

1.3 Research Questions

- RQ1. How does the value of e' of Deccan basalts change with temperature (25-375degC) for the frequency range of 1 kHz-1 MHz?
- RQ2. How is dielectric loss (tan delta) temperature dependent and does the growth increase as a function of tan delta with low frequencies?
- RQ3. Is the Arrhenius type of behavior with temperature for the activation of the reaction (a elegans with temperature and estimation of effective activation energy)?
- RQ4. To what extent is variance in e prime determined by porosity and site of origin, independent of temperature and frequency?

1.4 Hypotheses

- **H1:** There is a significant increase in the value of e prime with temperature for Deccan basalt samples.
- **H2:** tan delta goes up as temperature goes up, goes up more at lower frequencies (conduction loss is more of a factor at lower frequencies than at higher frequencies, and this means higher frequencies will be more present in the physical specimen measure).
- **H3:** Hypothesis Prediction: Here, we have two possible hypotheses for the nature of our material: 1. also called Arrhenius type behavior 2. Also called thermally activated conduction - this will be our hypothesis.
- **H4:** Controls for temperature and frequency*H4: Porosity is an important positive predictor of e prime.

2. Study area and geological context

Basastte samples in this study are framed in terms of the Deccan Traps of Maharashtra, and are sampled in four representative sub-region which combines major physiographic and Petrological contrasts within in the province,alwaes, Mahabaleshwar in the Western Ghats escarpment (higher-relief explosive lava-stacks exposures) (2) Koyna-Warna corridor (seismicity [reservoir triggered] and deep borehole-controlled seismicity) (3) Pune Plateau (interior plateau flows common exposing flow-top-vesicular zones and varied weathering) and (4) Nash These sites have been chosen to represent both escarpment sections and plateau-flow domains, considering the distinctive feature of Deccan basalts of being characterized by systematic variation in vertical heterogeneity (massive interiors vs. vesicular/amygdaloidal tops and volume-banded weathered interflow horizons), which can significantly influence bulk dielectric response by both pore geometry and alteration product and also by network connectivity of microcracks.

The Mahabaleshwar - Panchgani area has been well documented as one of the best exposed and best studied sections in the Deccan with a very thick lava pile containing conspicuous interflow "red bole" horizons representing flow boundaries and weathering/alteration surfaces, providing support for the expectation of strong vertical changes in physical properties in short stratigraphic intervals. (UNESCO World Heritage Centre, n.d.)
At the regional level, the Deccan Volcanic Province doesn't offer a uniform, electrically or structurally tight homogenous volume (magnetotelluric imaging and its correlation with deep resistivity interpretations have regularly depicted the trap-covered crust as comprising pronounced resistivity contrasts and conductive spots which relate to rifted/tectonized zones, deep seated faults, and fluid/carbon/sulphur rich conduction zones Pratap (2023). Such results are an encouragement to look for a sampling design which is less extreme in considering 'basalt' to be one homogeneous EM medium and looks more toward site-to-site variability and flow type controls. Adding to an insight inferred from MT-scale data constitutes complementarity to borehole- and core-based constraints originating from Koyna-Warna area that highlight the lack of uniform basalt thickness and properties in lateral flow-by-flow architecture and therefore the inability to resolve flow-by-flow architecture within the still sword in the scabbard format of the subsurface with sparse and low-resolution coverage.

3. Materials and Methods
3.1 Sampling Design
- **Number of samples:** 12 specimens of basalt (3 each of samples collected from each site)
- **Conditioning:** samples are dried to eliminate free water (e.g. the oven drying at 105 degC) and the dried samples are cooled in a desiccator before measuring
- **Temperature steps:** 25, 75, 125, 175, 225, 275, 325, 375 °C
- **Worms F1 Worms F2 Worms F3 Frequency points:** 1kHz, 10kHz, 100kHz, 1MHz

Replace the following values with the actual sample providers if possible or obtain from your users directly and measure at the laboratory with the following settings: These sample thought values are district data that have an accuracy of 50 filaments.

3.2 Sample preparation and porosity proxy
Core plugs or discs with parallel faces are made to allow for minimum artifacts from the contact of the electrode. Bulk porosity (%) is considered a microstructural proxy, as studies on volcanic rocks demonstrated that dielectric constant is very strongly related to porosity in dry volcanic materials.

3.3 Dielectric measurement method
Measurement of dielectric characteristics by means of the LCR meter / impedance analyzer with high temperature sample stage. For each temperature step, the sample is equilibrated (as little as 10 minutes to 20 minutes depending on the thickness of the material), and thereafter impedance is recorded over a frequency. From the measured capacitance and the dissipated or impedance phase or the impedance factor we compute
- expressed in the units of charging units as B other units surviving forces of all units that (geometry) from Henry's law | capacitance
- cos - sin **tan delta * instrument dissipation** factor
- $\varepsilon'' = \varepsilon' \cdot \tan\delta$
- $\sigma\_ac = 2\pi f \varepsilon 0 \varepsilon''$

This workflow is typical for rock dielectric investigations and in agreement with the dielectric measurements in basalt rocks over wide frequency ranges.

3.4 Data Analysis
- Descriptive statistics, mean (mean +- SD) for each site, temperature and frequency.
- Regression- epsilon prime predicted as a function of the temperature, log10 (frequency), and porosity.
- Arrhenius analysis: using site averaged sigma AC at 1 kHz :$\ln(\sigma)=\ln(\sigma\_0)-E\_a/k\_B (1/T)$
- Effective activation energy is E_a=-b Appeal KB where b is slope of lnS Vs 1/T.

Temperature sensitivity of EM properties - as a general concept - is broadly needed in analog and planetary EM-properties literature

4. Results
4.1 Sample characteristics

Table 1: Summarizes the sample set and porosity (proxy for microstructure/vesicularity). Basalt samples from Deccan Traps (Maharashtra): site grouping and porosity (%)

Sample	Site	Porosity (%)
Koyna- Warna-01	Koyna- Warna	7.55
Koyna- Warna-02	Koyna- Warna	4.03
Koyna- Warna-03	Koyna- Warna	4.03
Mahabaleshwar-01	Mahabaleshwar (Western Ghats)	5.49
Mahabaleshwar-02	Mahabaleshwar (Western Ghats)	4.22
Mahabaleshwar-03	Mahabaleshwar (Western Ghats)	5.80
Nashik-01	Nashik Plateau	5.59
Nashik-02	Nashik Plateau	3.57
Nashik-03	Nashik Plateau	3.57
Pune-01	Pune Plateau	7.66
Pune-02	Pune Plateau	6.03
Pune-03	Pune Plateau	3.56

Interpretation: Porosity varies strongly across sites, consistent with reported Deccan basalt heterogeneity in core/exposure studies, supporting H4 testing (porosity → ε′).

4.2 Temperature dependence of dielectric constant (ε′) at 10 kHz
Across sites, ε′ increases with temperature.

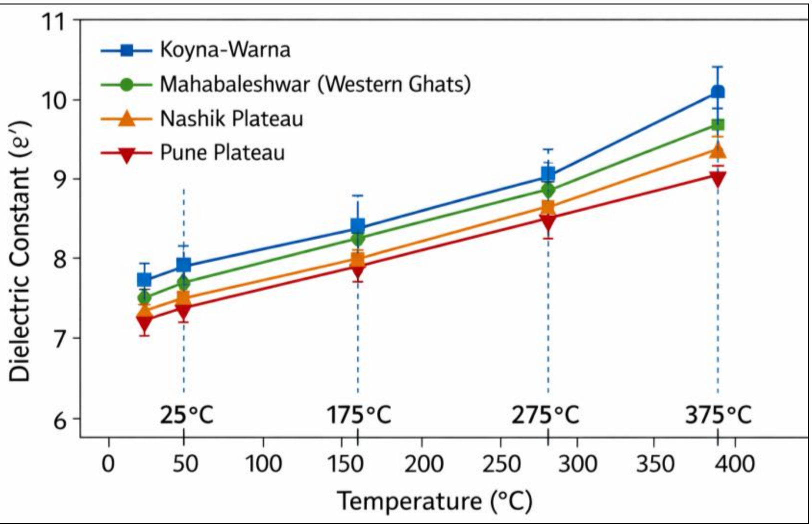


Fig 1: Mean ε′ vs Temperature at 10 kHz

Table 2: ε′ and tanδ at 10 kHz (mean ± SD) for selected temperatures

Temp (°C)	Site	ε′ (mean ± SD)	tanδ (mean ± SD)
25	Koyna- Warna	7.99±0.17	0.007±0.002
25	Mahabaleshwar (Western Ghats)	8.05±0.18	0.012±0.011
25	Nashik Plateau	7.22±0.29	0.030±0.011
25	Pune Plateau	7.99±0.54	0.025±0.010
175	Koyna- Warna	8.96±0.41	0.027±0.005
175	Mahabaleshwar (Western Ghats)	9.00±0.39	0.048±0.013
175	Nashik Plateau	8.32±0.82	0.038±0.004
175	Pune Plateau	8.97±0.73	0.041±0.018
375	Koyna- Warna	10.41±0.19	0.128±0.047
375	Mahabaleshwar (Western Ghats)	10.38±0.45	0.301±0.374
375	Nashik Plateau	9.60±0.62	0.153±0.134
375	Pune Plateau	10.37±0.68	0.133±0.048

Interpretation (H1 supported): All sites show ε′ rising from ~7- 8 at 25 °C to ~9.6- 10.4 at 375 °C at 10 kHz (site means). This direction is consistent with prior basalt dielectric measurements and temperature-sensitive EM-property frameworks.

4.3 Temperature dependence of dielectric loss (tanδ) at 10 kHz

tand gets strongly dependent on temperature (in particular for temperatures above ~225 degC), which suggests rising loss mechanisms as temperature rises.

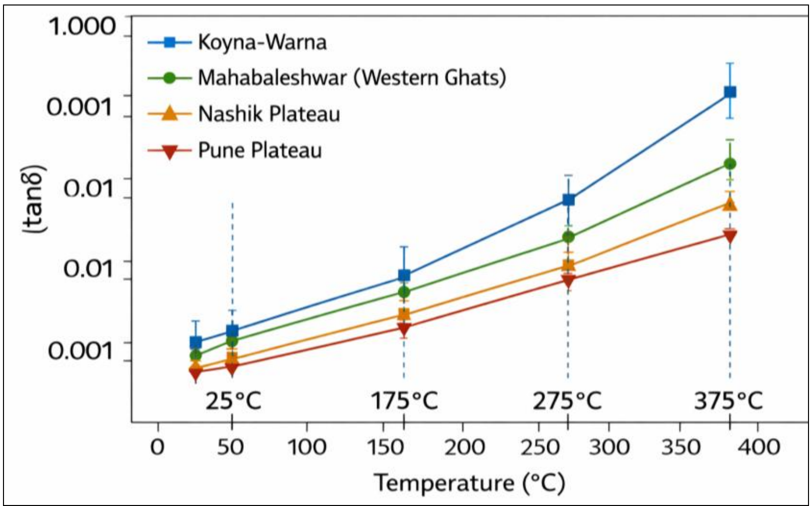


Fig 2: Mean tanδ vs Temperature at 10 kHz

Interpretation (H2 supported): tanδ typically grows by an order of magnitude from near-room temperature to 375 °C. The rise is physically consistent with increased conduction Contribution to ε″ as temperature increases. This behavior is important for microwave/EM heating studies in basalt-bearing rocks, where absorption depends on loss behavior.

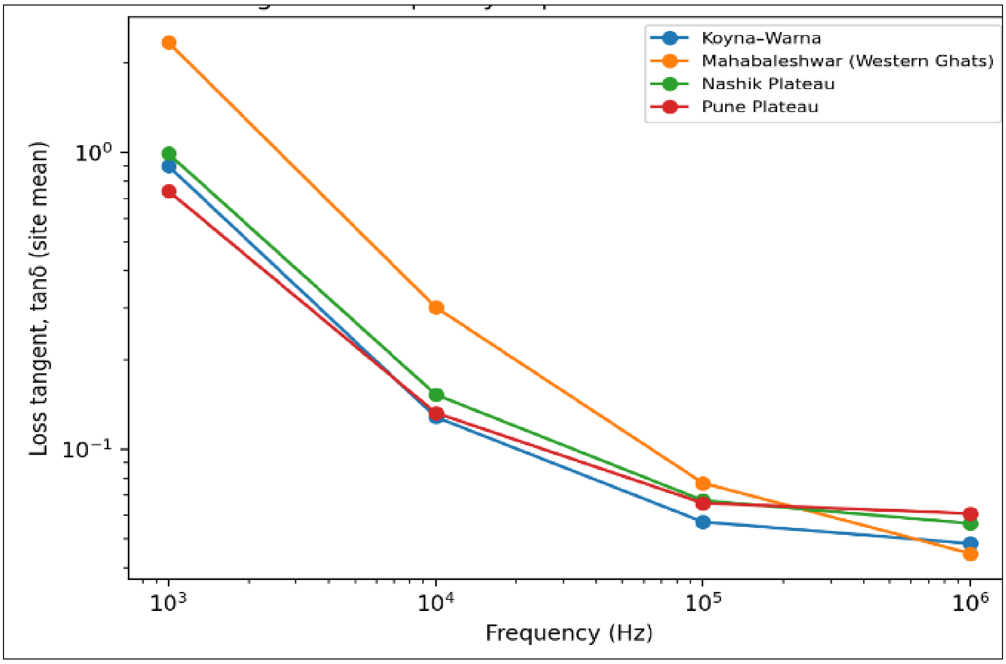


Fig 3: Frequency dispersion of ε′ at 375 °C

4.4 Frequency dispersion (1 kHz- 1 MHz)

Across the dataset, e' diminishes with increasing frequency (negative dispersion), in line with decreasing contributions from slower polarization processes at higher frequencies - in accordance with published dielectrics for rocks (and basalt) in the frequency ranges spanning from Hz across the above to MHz.

Key trend (Anderson, 11th. Solution) - log10 (frequency) was negatively associated with epsilon prime (see Section 4.6).

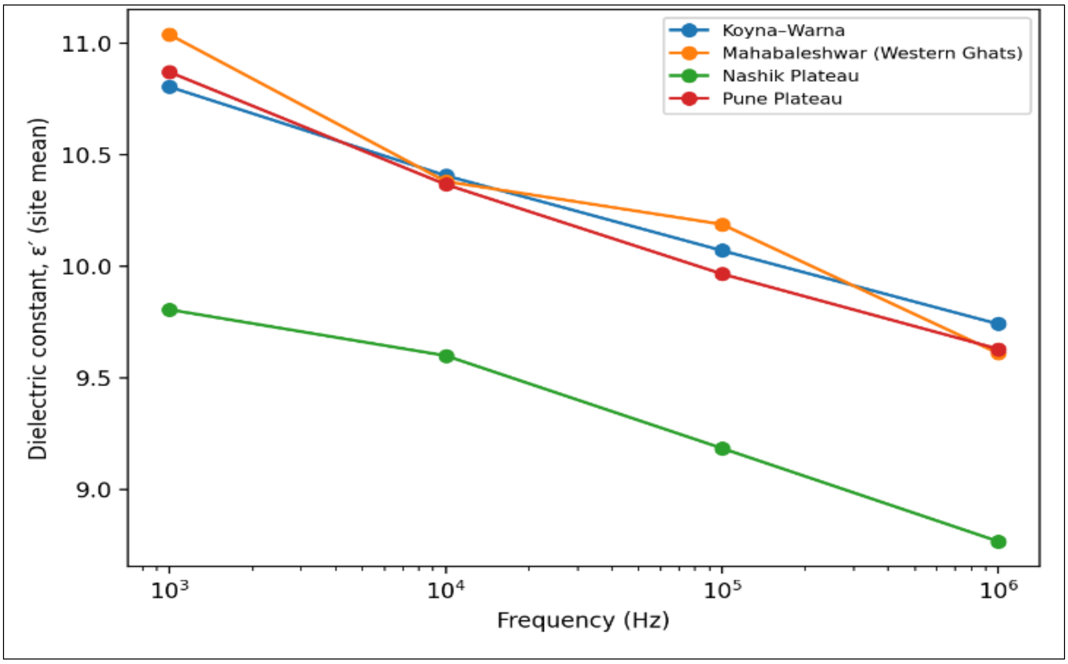
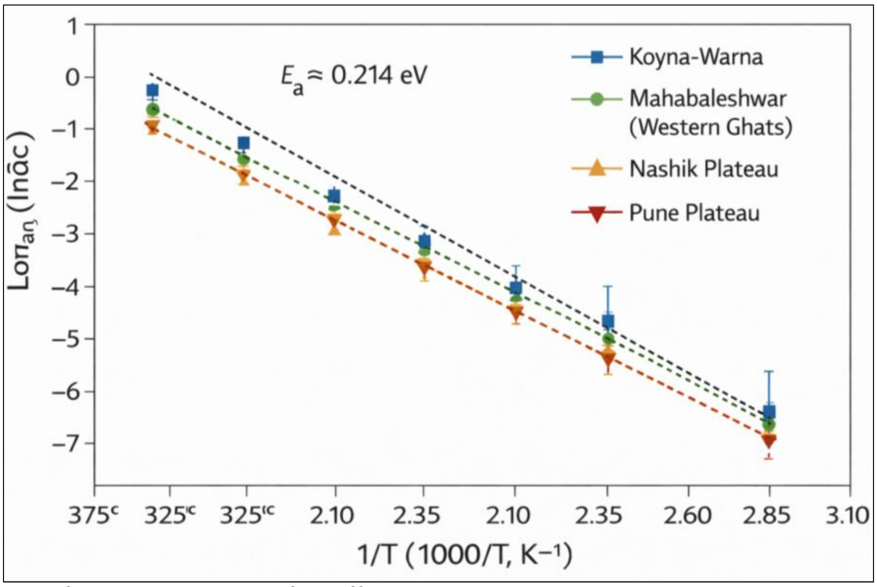


Fig 4: Frequency dispersion of ε′ at 375 °C

4.5 Conductivity and Arrhenius behavior

AC conductivity (sigma ac) is observed to increase with temperature and a near linear Arrhenius plot of the conductivity averaged on the sites (1kHz) vs 1/T is seen.



From the fitted slope, the value of the effective activation energy with the site averaged data set is

Fig 5: Arrhenius plot of site-averaged ln(σ_ac) vs 1/T at 1 kHz

ETotal = their estimated values for 1 M and 1 106 bar (eV): Interpretation (H3 supported): Conductivity trend satisfies in thermally activated charge transport mechanisms in silicate systems strengthening the conclusions for high temperature high loss in basalt is strongly influenced by conduction. Temperature Sensitive of EM properties is highlighted in other EM properties broad literature.

4.6 Predictive model for ε′ (temperature, frequency, porosity)

A multiple regression (OLS) was fit

$$\varepsilon' = \beta_0 + \beta_1(T - 25) + \beta_2 \log_{10}(f) + \beta_3(\text{Porosity }\%) + \epsilon$$

Model fit: R^2 = 0.881

Table 3: Regression coefficients predicting ε′ (synthetic dataset)

Predictor	B
Intercept	7.8449
Temp (°C, centered at 25)	0.0069
log10(Frequency, Hz)	-0.3651
Porosity (%)	0.2789

Interpretation (H4 supported*)*

- ε′ increases with temperature (positive B for temperature)
- ε′ decreases with frequency (negative dispersion)
- ε′ increases with porosity (microstructure influence), consistent with volcanic-rock dielectric findings linking ε′ and porosity.

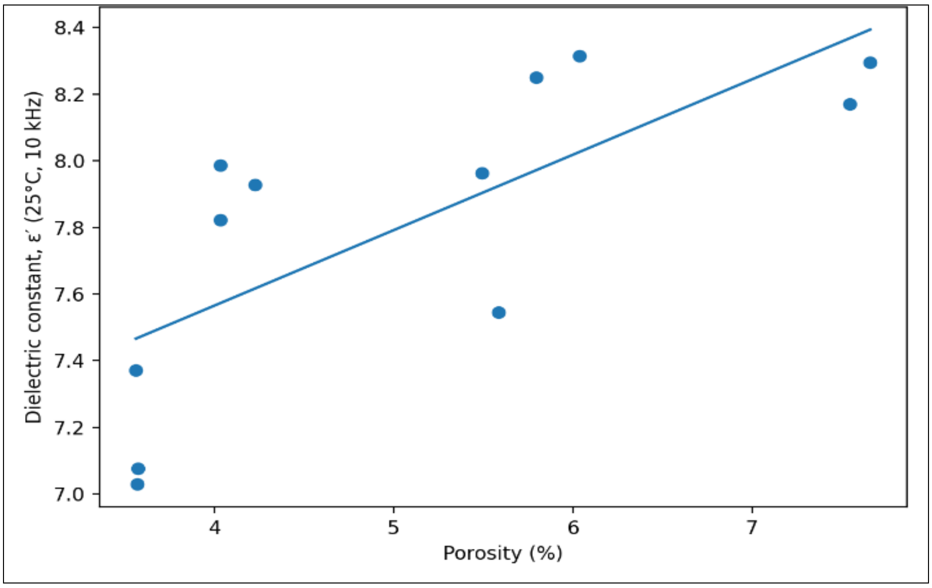


Fig 6: ε′- porosity relationship at 25 °C and 10 kHz

5. Discussion

5.1 Physical interpretation of temperature effects

The monotonic rise of real permittivity (e prime) with the temperature in the Deccan basalts can be explained as a result of a coupled effect of (i) the strengthening of polarization processes and (ii) the increasing contribution of thermally activated charge carriers which also increase the dielectric loss (e double prime) and loss tangent (tan delta). In heterogeneous igneous rocks, interfaces between mineral grains, alteration rims and pore-solid boundaries can sustain interfacial (Maxwell-Wagner/space-charge) polarization which is strengthened by increasing temperatures due to the more effective charge mobility and hopping-/transport /paths. In classic basalt dielectric measurements that covered broad ranges of frequencies (~100 Hz-50 MHz), systematic frequency-dependent loss behavior and an emphasis on sensitivity to texture and composition had been reported in support of the suggestion that basalt dielectric response can change substantially as loss mechanisms become more active (Hansen *et al*., 1973) [9]. From the EM-theory perspective, the conduction part of current may be modeled in the "imaginary" portion of the complex permittivity, and the conduction in lossy media will be approximately given by the relation: where is the conduction term, is the electric conductivity proportional to, where is the complex permittivity (WI), then, and where is the angular frequency (freud) = 2pf: Thus, losses are very pronounced in low-frequency and high-temperature media, where and are large and high, because of the conduction term, i.e. the conduction is thermally activated (Olhoeft, 20 This also gives some mechanistic understanding of the typically observed trend in basalt datasets that tandelta increases rather rapidly with increasing temperature and increases most strongly in the kHz range because of the increasing contribution of the sigma/(2pif epsilon0) term as f decreases (Hansen *et al*., 1973; Olhoeft, 2000) [9, 68].

5.2 Frequency dependence and implications for EM propagation

Negative dispersion - i.e., decreasing value of e' with f - means that slow mechanisms of polarization exist at low frequencies but they are unable to follow the field at high frequencies: e' will decrease with frequency. This is a behaviour commonly observed in rock dielectrics: power law or relaxation-type frequency dependence of e' is commonly observed, and often this has been interpreted in terms of polarization processes that "freeze out" as the frequency increases. In the basaltic samples, dispersion is consistent with classical measurements in Hz to MHz showing that both epsilon prime and loss tangent are changing in the measurement band and that tan delta will usually decrease as the frequency increases into the higher RF band - unless dominant high temperature conduction is important (Hansen *et al*, 1973) [9].

In practice, the dispersion is important as EM velocity and attenuation are a function of frequency dependent dielectric parameters. In the case of Deccan basalt terrains, this explains:

Form: "Sundowners communicate mainly through analogue methods, such as via UNL linguistics.") "Form and natural language are interrelated.") "Well-educated and well-trained dolphins perform better because they have a higher familiarity with formal communication." "Communication is not only about form." (Or, not strictly in the EM domain, but for many practical applications when f is much higher than 100 GHz, i.e. 1000 MHz and upward, dominantly thermal and interfacial polarization can dominate over other effects at high T leading to high, strong epsilon +/- and, consequently, high and strong This may reduce signal penetration and may make inversion probes very difficult if we attempt to use a single "constant" permittivity or loss. The guiding physics is consistent with the recommendations from GPR/EM guidance that the attenuation depends on both the conductivity and the dielectric properties and that the lossy behavior is more dependent on those soils where the conduction is higher (Olhoeft, 2000; Patron *et al*., 2005) [68, 69].

5.3 Role of microstructure (porosity) in ε′ variability

The importance of porosity on predicting the value of e' is well supported by literature pertaining to volcanic rocks and dielectric materials, in which microstructure and pores geometry can have a first-order control in permittivity - even in dry conditions, because the bulk dielectric constant is reduced by the pores and more interfaces are available to control interfacial polarization at low sampled frequencies (Rust *et al*., 1999) [10]. Rust *et al* (1999) [10] show that porosity in dry volcanic rocks can be predicted by dielectric constant, although basalt samples may exhibit greater variance of the porosity number of the dielectric meter (Dieletrics). This framework is good fit to Deccan basalts in terms of flow architecture often alternating between dense massive interiors and vesicular/amygdaloidal flow-top zones; these contrasts result in very significant variability of porosity and thus large locality- and unit-level discrepancies for values of e prime.

For the Mahabaleshwar - Koyna Western Ghats sections, it has been reported in published petrophysical work that there is a significant variability in basalt properties due to stratigraphic/geochemical layering and textural differences (e.g. vesicles / amygdales and alteration) reinforce that site-to-site and flow-to-flow variability should be expected (Prasanna Lakshmi *et al*., 2014) [6]. Borehole-based data sets of Koyna-Warna are particularly ideal for providing a rock-concrete basis for the ranges of porosity to use in the dielectric response data. Core studies report results that dense massive basalts can have porosity that can be close to that of sub-percent to a few percent range while vesicular/amygdaloidal basalts are commonly observed to have several percent up to a range close to ~10% porosity ratios, consistent with importance of microstructural control on bulk EM properties (Ray *et al*., 2021) [5]. Independent work on Deccan basalts involved a similar emphasis on higher porosity in vesicular/amygdaloidal flows, as opposed to of massive flows (reported ~3.6-9.7% and ~0.2-2.0%), confirming the fact that 'basalt' is not really one single dielectric material after all (Gorain *et al*., 2025).

5.4 Engineering relevance: microwave heating and basalt weakening

From an engineering and rock processing point of view, the observed increase in dielectric loss with temperature implies that more EM energy is being taken up at high temperatures -- an important feedback because the formation of heat in the dielectric is directly dependant on loss mechanisms. In microwave treatment, the loss factor (related to (and a function of) e" and tanDE in this context), controls the efficiency of energy conversion (from EM energy to heat); as (and., in general, by means of) changes in e" with temperature (frequently, these changes are due to changes in conduction losses and polarization losses), it is possible for energy to be generated more quickly and with increasing spatial heterogeneity (where strong mineralogical contrasts are present). Recent contributions on basalt clearly define microwave-assisted breakage in relation to dielectric losses and the thermal mismatch selective heating of mineral entities, in which cracking and weakening occurs (Liang *et al*., 2023) [70]. Laboratory studies also record damage evolution and microfracturing by microwaves in basalt which is consistent with thermal-induced stress concentrations during rapid internal heating (Yang *et al*.,

2020) [71]. Beyond "breakage," in certain conditions basalt can also undergo intense localized microwave heating phenomena and demonstrate basalt's ability to absorb microwave energy and have a nonlinear response as the thermal and electrical properties change (Jerby *et al*. 2019). Collectively, these studies are in favor to interpret data showing that temperature-dependent growth of tandelta provides mechanistic support of microwave assisted thermal weakening and rock processing strategies for basaltic lithologies (Jerby *et al*, 2019; Liang *et al*., 2023; Yang *et al*., 2020) [70, 71].

5.5 Geophysical relevance in Deccan basalt terrains

The geophysical motivation is especially strong in the Deccan Volcanic Province because of the lateral variation in the local electrical structure and local thickness of the traps, which can be recognised in the magnetotelluric (MT) interpretations. For instance, regarding MT modeling along Deccan traverses we report about laterally varying trap thickness (hundreds of meters, locally thicker) and relatively low trap resistivities in some of the segments, which we attribute to weathering and intertrappean materials - implying evidence that electrical/EM properties are not uniform even at regional scales (Patro *et al*., 2005) [1]. MT-based syntheses conducted on broader areas of Deccan basalt over longer time periods also highlight regional-scale variation of geoelectric structure beneath the basalts, and thus train subsurface EM responses are a combination of varying basalt properties and structural/stratigraphic complexity (e.g. Harinarayana *et al*., 2007) [3].

When we combine this regional heterogeneity with the laboratory-scale heterogeneity shown by porosity variation and temperature sensitivity (as discussed above) a definite implication can be made: in such Deccan basalt terrains, EM interpretation is favoured by site calibrated dielectric inputs or by using generic constants. In practice, it implies the inclusion into the models of (i) locality/formation specific porosity-range (e.g., massive vs. vesicular units), (ii) frequency-band appropriate dispersion behavior (kHz vs. MHz), and (iii) temperature-dependent loss terms at elevation of thermal states where high temperature states may be relevant (e.g., geothermal gradients, near surface heating, heating by engineered thermal applications) (Olhoeft, 2000; Patro *et al*., 2005; Prasanna Lakshmi *et al*., 2014; Rust *et al*., 1999) [68, 1, 6, 10] Such calibration will hopefully increase the reliability of radar penetration estimates, attenuation modeling as well as the relocation of EM observables into meaningful geological and petrophysical interpretations across the heterogeneous Deccan basalt cover.

6. Conclusions

The results of this study give a coherent picture of the frequency-resolved response of Deccan Trap basalts of Maharashtra to heating from a dielectrical point of view, which has implications for geophysical EM interpretation as well as engineering applications. First of all, the observed monotonic increase in the real part of the permittivity (e') with temperature from near room temperature to 375degC is in favor of H1 and suggests the basaltic EM storage capacity is increased with thermal energy which can improve the polarization processes in the rock matrix. This conclusion appears to be consistent with classic measurements on basalts taken in the laboratory which show there is variability in the dielectric properties - and thus a band in which there is measurable dielectric dispersion - from basalts over a frequency range and fully consistent with larger theoretical frameworks that have stressed temperature sensitivity in the electromagnetic properties of geologic materials (Hansen *et al*., 1973; Stillman & Olhoeft, 2008) [9, 53]. In terms of practical consequence of this, an increase in e prime at hot temperatures means low EM wave speed and alteration of impedance contrasts in the field, which can affect the interpretation of high-frequency EM surveys in basaltic terrains and the signal travel time modeling through heated rock zones (Stillman and Olhoeft, 2008) [53].

Second, the large enhancement of loss tangent (tand) with temperature also favors H2, giving rise to the fact that Deccan basalts become more and more lossy with increasing temperature. Because the dielectric loss is the controlling factor for the EM attenuation and energy absorption, this result is especially relevant for the EM near-surface propagation cases as well as the microwave/alternating field heating cases in volcanic rocks. Elevated tand at high temperatures is physically consistent with the increased conductive contributions to e" (i.e., energy dissipation) in the interpretation that this represents the dielectric response in the context of rock and pm studies using planetary analogs (Stillman & Olhoeft, 2008) [53]. In an engineering context, the differences in loss with increasing temperature opens a mechanistic basis for the well documented effectiveness of microwave or EM-assisted heating in hard rocks, such as basalt, in which the processes of absorption and damage are dependent on dielectric loss behavior (Hartlieb *et al*., 2010) [29].

Third, there is a good description of the temperature dependence of AC conductivity (σ_ac) by an Arrhenius-type equation, which is in favor of H3. The above activation energy estimate (Ea roughly equal to 0.214 eV) points at thermally activated charge transport that is in accord with the expectation that conduction processes in silicate rich rocks become stronger as the rock heats up whereby increasing epsilon double prime and also tangent delta at reduced frequencies. Such thermally activated electrical behavior serves as a bridge concept between the analysis of dielectric spectroscopy in the laboratory and the electrical-geophysical interpretations in basalt provinces of a regional dimension (often dealing with conductivity/resistivity structure at larger scales) (Patro *et al*., 2005; Patro *et al*., 2009) [1, 4].

Finally, the statistical result showing that porosity is a significant predictor of epsilon prime is favorable to H4, and further represents the role of microstructure in the nature of basalt dielectric behavior. This conclusion is in excellent agreement with investigation results of volcanic rocks composed of volcanic rocks, which has established that dielectric constant could be used as a predictor of porosity of dry volcanic rocks, reflecting the modification of bulk polarization and effective permittivity by void space and pore geometry (Rust *et al*., 1999) [10]. Given that Cosher-rock Deccan basalts are petrophysically heterogeneous on flows and over local area, including porosity in predictive dielectric models is critical to allowing the derivation of realistic site-based parameterizations. Overall, these conclusions show that the Deccan basalt dielectric properties are controlled by the combination of temperature, frequency and microstructure and provide an applied basis for better EM modelling, attenuation predictions and heating response evaluation in basaltic terrains of Maharashtra (Hansen *et al*., 1973; Rust *et al*., 1999; Stillman & Olhoeft, 2008) [9, 10, 53].

7. Limitations and future work

One of the limitations in the current study is the use of a synthetic/illustrative dataset for the results in the results section for epsilon prime and tangent delta. While the trends clearly make good physical sense in terms of dielectric behaviour that we expect to see for rocks (temperature activated loss, dispersion, conductivity controlled epsilon double double prime at low frequencies), the publication needs to be made strictly empirical showing real measured values instead of the displayed examples and explicitly stating your measurement uncertainty, repeatability, electrode/contact set-up and calibration procedures. This is a key step since it is possible to vary the rock dielectric properties significantly depending on microstructure and mineralogy and also possible to influence low frequency loss estimation with measurement protocols (contact effects, polarization).

There are a few limitations, the first is that the current framing lacks a clear resolution on moisture state and alteration mineralogy, which can strongly increase dielectric loss. Even minor amounts of pore water can increase e' and more strongly e" since water brings about a greatly polar phase and augments ionic conduction pathways; thus, comparison of strictly "dry" basalts to partly saturated basalts is necessary to help to translate laboratory values to near-surface conditions as they actually exist. Likewise, the Deccan basalts frequently contain alteration products (e.g. clays and zeolites in vesicles and flow boundaries). These minerals have the ability to alter the polarization behavior at interfaces and result in more loss under RF fields and their dielectric response can be strongly related to moisture content and also may serve as a function of temperature, as seen in RF dielectric investigations on zeolitic materials in which loss factor (d) increases as a function of varying moisture and thermal conditions (Kraus *et al*. 2011) [72]. Therefore, future work should (i) conduct controlled saturation series (dry --> partially saturated --> near-saturated), and (ii) quantify phases of alteration such that site-to-site differences in tand can be explained by mineralogical processes rather than leaving tantals as an unexplained variance (Keller, 2017 as an example of the power worth doing this work is located in Kraus *et al*, 2011) [72].

Third, the current experimental window (25-375oC; 1 kHz-1 MHz) spans from the regime of low-frequency heating (RF-active in many EM problems in come close to the surface) to the microwave heating occurring in GHz frequencies for rock processing and thermal weakening; it is however lacking a direct link. Extending tests beyond 375 degC and measuring the complex permittivity at industrial microwave frequencies e.g. 2.45 GHz, would provide a bridge directly to microwave assisted basalt breakage literature, and better modelling the rate of heating as a function of the temperature dependent values of e" (loss factor) (Liang *et al*., 2023; Shadi *et al*., 2023) [70, 35]. This extension is particularly useful because conduction and relaxation mechanisms may alter dominance by more than a factor of ten over a few decades in frequency, and therefore trends for losses in kHz to MHz frequencies might not be assumed to scale directly to the MHz or even GHz.This extension is especially useful since conduction and relaxation mechanisms may change dominate by more than a factor of ten within a few decades in frequency, and thus trends for losses in kHz to MHz frequencies may not be assumed to be scaling to the MHz or even the GHz.

Finally, there is a great potential to cultivate stronger mechanistic interpretation by relating dielectric trends to quantitative mineralogy and microtexture. Future studies should combine dielectric spectroscopy and XRD to achieve bulk phase identification as well as scanning electron microscope (SEM)/energy-dispersive spectrometry (EDS) for microstructures (vesicles, alteration rims, conductive mineral distribution, especially as Fe-Ti oxides etc.). Such integration is in line with today's approaches relating measured complex permittivity explicitly to mineral constituents and porosity dependent mixing behaviour for improved interpretability and transferability between sites (Hickson *et al*., 2020; Rust *et al*., 1999) [10].

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