ELECTRICAL PROPERTIES OF BLACK SCHIST FROM THE HIMALAYAS OF CENTRAL NEPAL

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ABSTRACT

Our study is focused on rocks from a shear zone located in the Himalayas of central Nepal, 60 km north of Kathmandu. The whole region was heavily affected by the deadly Mw7.8 Gorkha earthquake in 2015. The shear zone is associated with outcrops of black schist and large CO_2 discharges with a metamorphic isotopic signature.

We analyzed the frequency-dependent, complex, electrical conductivity of the black schist and an old augen gneiss, both collected in the shear zone. The electrical conductivity of both cores and crushed material was measured. Cores were drilled parallel and perpendicular to the natural foliation in order to investigate local electrical anisotropy.

We carried out laboratory measurements of the complex electrical conductivity, thereby focusing on anisotropy, salinity dependence and the impact of carbon dioxide on the electrical properties. The augen gneiss shows the expected low polarizability and moderate conductivity, which is dominated by the pore-filling brine. It shows a weak anisotropy. By contrast, the black schist possesses extraordinary high polarizability and, consequently, a high conductivity. Its anisotropy is very pronounced.

Understanding the anomalous conductivity of the Himalayan black schists provides valuable information, which might help to interpret the results of deep crustal MT surveys and reveal the nature of the Himalayan orogeny. Furthermore, understanding the physics of conductive phases in metamorphous rocks in the presence of CO_2 opens important new perspectives in numerous applications.

INTRODUCTION

The Himalayan Range, frequently affected by large earthquakes, results from the collision of the Indian plate with Eurasia. The tectonic process essentially takes place along a single subhorizontal fault, the Main Himalayan Thrust (MHT). The MHT exhibits a ramp, which blocks all motion, except during large earthquakes. The so called Main Central Thrust (MCT) shear zone is located approximately 60 km north to Kathmandu (Nepal). It belongs to the Lesser Himalayan Sequence (LHS). The MCT places high-grade metamorphic rocks of the Greater Himalayan Sequence, located northward, over low-grade metamorphic rocks of the LHS (see Fig. 1).

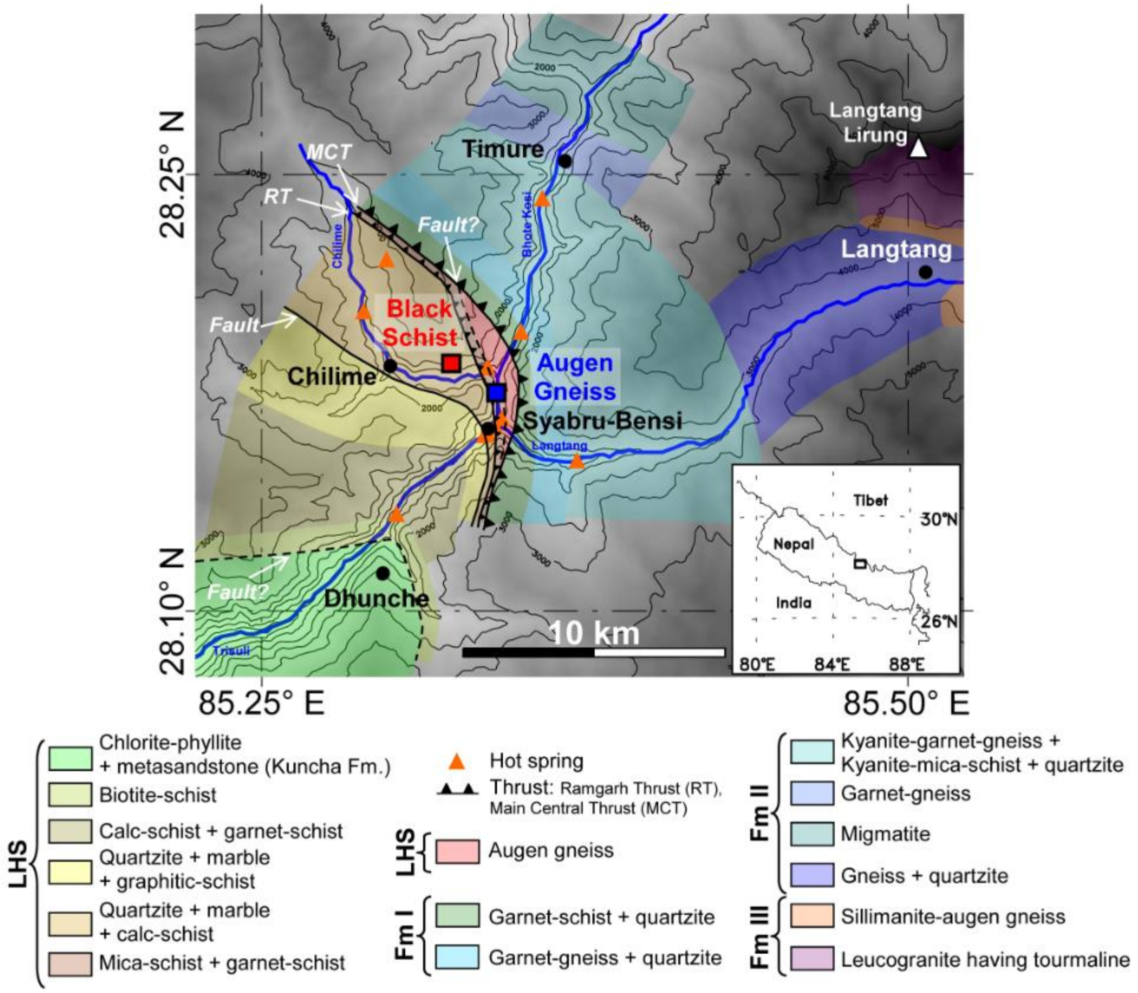

Fig. 1: Geological map of the upper Trisuli and Langtang valleys (central Nepal) showing the sampling locations in the Lesser Himalayan Sequence (LHS). The inset shows the sampling area in Nepal. (geology taken from various sources, see [1] and references therein, courtesy of Laurent Bollinger).

Two decades ago, a magnetotelluric (MT) sounding profile perpendicular to the MHT and MCT revealed a conductive zone associated with seismic activity at a depth of 10 to 15 km (e.g. [2]). Appart from recent investigations, which aim at the reproducibility and numerical stability of said anomaly, different explanatory approaches are available to explain the presence of a deep conductive zone. The zone might be associated either with the presence of highly conductive brines or with the increased occurrence of conductive phases such as graphitic mineralization (e.g. [3]).

More recently, large CO_2 discharges with a metamorphic isotopic signature were discovered [4], and studied in detail on the surface near the location of the conductivity anomaly. The combined observations suggest that carbon, indeed, could account for the observed mid-crustal conductor or at least play an important role in the crustal conductivity structure of the area.

To evaluate this possibility, we analyzed the electrical conductivity of Himalayan rock samples collected in the CO_2 degassing area north of Kathmandu, in the region affected by the deadly Mw7.8 2015 earthquake. We investigated two characteristic rock types of the MCT shear zone: a coarse-grained, quartz-feldspar-biotite-muscovite-tourmaline augen gneiss, and a biotite-rich, black mica-schist. We carried out laboratory measurements of the complex electrical conductivity of the Himalayan rocks, thereby focusing on anisotropy and salinity dependence. Understanding the anomalous conductivity of the Himalayan black schist may provide valuable information, which might help to enhance both the interpretation of deep crustal geophysical surveys and our understanding of the Himalayan orogeny.

MATERIALS AND METHODS

The Himalayan sequences are dominated by high- and low-grade metamorphic rocks. We investigated two characteristic rock types of the Main Central Thrust (MCT) shear zone. The focus of the laboratory study was on the electrical properties of a biotite-rich, black mica schist, which contains 4 to 8% of graphite. For comparison, we also investigated a quartz-feldspar-biotite-muscovite-tourmaline augen gneiss, which is common in the area of interest.

The electrical properties of the rocks were investigated by laboratory measurements of the complex and frequency-dependent electrical conductivity σ (spectral induced polarization method, SIP). The experimental set-up, which is capable of measuring the SIP response under both normal and reservoir conditions, is described in [5]. The resulting conductivity data contains information on both electrolytic conduction (σ_{el}) and polarization effects (σ_{surf}):

$$\sigma^*(\omega) = \sigma_{\mathrm{el}} + \sigma^*_{\mathrm{surf}}(\omega) \qquad (1)$$

Here, ω denotes angular frequency and the asterisk marks complex quantities. The two conduction mechanisms occur simultaneously and form the bulk conductivity, which may be described by a real and an imaginary part (σ' and σ'', respectively) or by a magnitude and phase shift ($|\sigma|$ and φ, respectively). Both formulations are equivalent to one another:

$$\begin{aligned}\sigma^*(\omega) &= \sigma'(\omega) + i\sigma''(\omega) \\ &= |\sigma^*| \cdot e^{i\varphi} \\ &= \left[\sigma_{el} + \sigma'_{if}(\omega)\right] + i\sigma''_{if}(\omega) \qquad (2)\end{aligned}$$

We used core samples, drilled both parallel and perpendicular to the natural foliation of the rocks, as well as crushed samples. The supplementation of our investigations by crushed samples allows for a better understanding of the conduction mechanisms within the rock and for an efficient realization of multi-salinity experiments of rocks, which are very low-porous in their consolidated state. In addition, measurements on black schist – quartz sand mixtures were carried out in order to investigate the mass fraction of black schist, which is necessary to dominate the bulk properties. Exemplary experiments in a CO_2 atmosphere at elevated pressure were conducted to assess the impact of CO_2 on the SIP response of the investigated rocks.

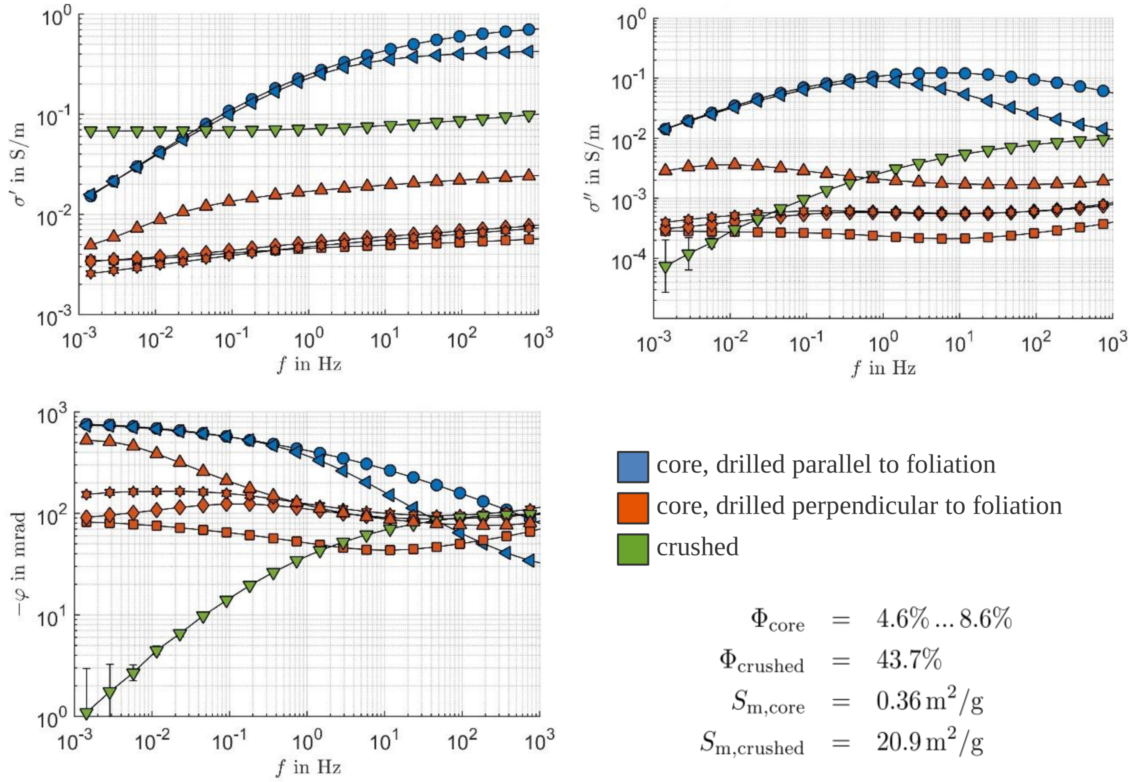

Fig. 2: Frequency-dependent complex conductivity of the black schist in terms of real part conductivity (top left), imaginary conductivity (top right) and phase shift (bottom left). All samples were saturated with a NaCl solution with a conductivity σ_w=0.1 S/m. The porosity Φ and the specific inner surface area of both cores and crushed material are given in the bottom right panel.

RESULTS

The black schist investigated in the laboratory shows highly anomalous electrical properties. The conductivity data of various cores and the crushed samples in shown in Fig. 2. Generally, the black schist is very conductive given its low porosity. At the same time it is extremely high polarizable, which shows up in the high imaginary conductivity and phase shift.

Conductivity is strongly dependent on frequency, which means that a black schist formation may appear differently at different frequencies (and therefore depths after inversion) of electromagnetic surveys such as MT or CSEM (controlled source electromagnetics). The very pronounced polarization and surface conduction is probably due to the presence of graphite.

A crushing of the sample causes an averaging of both real and imaginary conductivity at high frequencies. At the same time, the low frequency response is lost due to crushing. This implies, that a large part of the electrical conduction is associated with the texture of the solid core material, which is destroyed during crushing. Measurements on black schist – quartz sand mixtures demonstrated that already rather low mass fractions (appr. 25%) of black schist can dominate the bulk properties of the whole material.

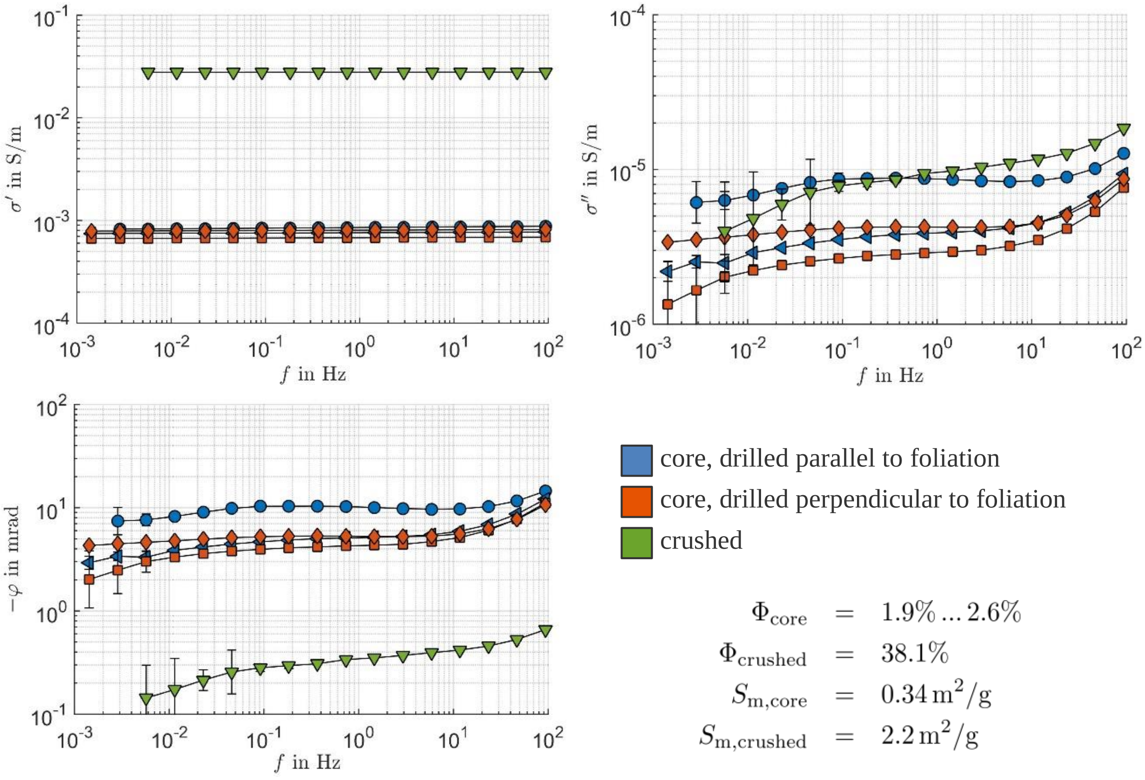

Fig. 3: Frequency-dependent complex conductivity of the augen gneiss in terms of real part conductivity (top left), imaginary conductivity (top right) and phase shift (bottom left). All samples were saturated with a NaCl solution with a conductivity σ_w=0.1 S/m. The porosity Φ and the specific inner surface area of both cores and crushed material are given in the bottom right panel.

The anisotropy of the black schist is very pronounced for both real & imaginary conductivity (factor 50 at 1Hz). Depending on the direction of the foliation both magnitude and frequency characteristics of the conductivity components change significantly. This means that black schist structures may show a strongly directional conductivity during geophysical imaging.

The measurements of the black schist indicate that the graphite is arranged according to the foliation without forming connected bands. If connected bands were present, this would show up as a strong ohmic (i.e. real-valued, frequency-independent) conductivity contribution. Since the polarization effects dominate the black schist properties, the graphite seems to be disseminated and only loosely aligned along with the foliation.

For comparison, the abundant augen gneiss was investigated, the results are plotted in Fig. 3. Compared to the black schist, the augen gneiss shows –as expected – a low conductivity, which is dominated by electrolytic processes. Its imaginary conductivity is small and the frequency dependence is weak, which indicates that polarization effects are moderate. It is also evident, that the crushing procedure has only little effect on the imaginary conductivity. This observation leads to the conclusion that the polarization effects present in the augen gneiss are driven by bulk volume effects and do not depend on the texture of the solid material.

Despite the macroscopically visible foliation, the electrical anisotropy of the augen gneiss is rather weak. Although a small tendency to higher conductivity and polarization along the foliation may be seen, it is in the same range as the individual variety of the core properties and cannot be considered significant. Except for a potential large scale fracture anisotropy, the gneiss may be considered as isotropic from the electrical point of view.

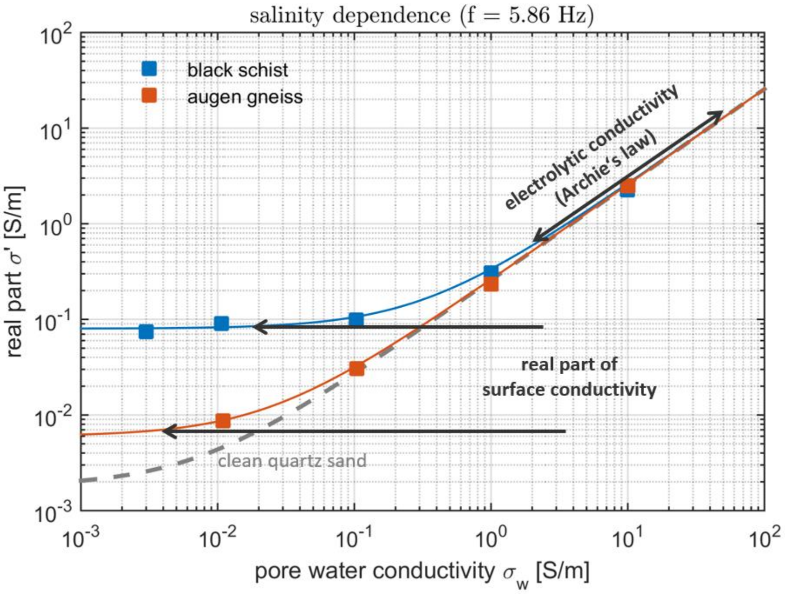

Fig. 4: Salinity dependence of real part conductivity derived from multi-salinity experiments on crushed samples. The Archie region and the real part of the surface conductivity (cf. Eq. 2) are indicated [6,7].

The dominance of electrolytic conduction in the augen gneiss implies that inferring brine conductivity from electrical measurements (for known porosity and temperature) should be well possible. To further investigate the relationship between water conductivity (i.e. salinity) and conductivity we carried out multi-salinity measurements on crushed samples of both black schist and augen gneiss.

The results are shown in Fig. 4 in terms of the real conductivity at 5.86 Hz. The curve of a typical clean quartz sand is shown for comparison. The slope of the curves at high water conductivities represent the formation factor whereas the intercept with the y-axis (appears as horizontal asymptote at low water conductivities) is the real part of surface conductivity.

The investigations show, that both black schist and augen gneiss have a comparable formation factor, which is due to the similar porosity and particle size of the crushed samples. The real part of the surface conductivity is however very different for both rocks. The augen gneiss exhibits a low surface conductivity - as found in the complex conductivity as well – and is mainly dominated by the Archie behaviour. As expected, it is well possible to relate water and bulk conductivity.

On the other hand the black schist shows an extremely high real surface conductivity, which dominates bulk conductivity over a wide range of salinities. In presence of the black schist, a high formation conductivity might consequently be misinterpreted in terms of brine conductivity if the surface conduction and polarization effects are not taken into account.

Exemplary experiments with the water-saturated, crushed rocks under CO_2 at 5MPa hydrostatic pressure for 5.5 to 7 days demonstrated the change in electrical properties due to the interaction of the rocks with CO_2. The real conductivity strongly increased for both rocks due to CO_2 dissolution and dissociation and the heavy mineral dissolution starting under pressure. The imaginary conductivity in- or decreases due to CO2 depending on pH-variation and mineral dissolution [5,8]. The strong reaction of the real conductivity causes a decrease in phase shift in all cases.

CONCLUSION

The investigated rocks possess anomalous and highly indicative electrical properties. The black schist is highly conductive also at low salinities or mass fractions due to the dominating surface conduction. This implies that black schist formations could appear as conductive anomalies in large scale MT surveys. Such high conductivity might be misinterpreted as brines, when the surface conduction is neglected. The strong anisotropy and frequency dependence has to be considered for black schist formations. The complex conductivity measurements suggest that the graphite is disseminated within the black schist but with a preferred orientation along the natural foliation.

The augen gneiss on the other hand is characterized by a strong domination of electrolytic conduction and low surface conduction. Consequently, gneiss formations are more sensitive to changes in formation brine salinity and effects of surface conduction are probably negligible on a large scale. The laboratory evaluation will enhance our understanding of the anomalous conductivity of the Himalayan rocks and will provide valuable information, which might help to reveal the nature of the Himalayan high conductivity zone.

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