The Influence of Magnetic Minerals on Induced Polarization Measurements in Sedimentary Rocks

Klaudio Peshtani1, Andreas Weller2, Sina Saneiyan3, and Lee Slater4

1Department of Earth and Environment Sciences, Rutgers University Newark, Newark, NJ, USA; 2Institut für Geophysik, Technische Universität Clausthal, Clausthal-Zellerfeld, Germany; 3School of Geosciences, University of Oklahoma, Norman, OK, USA

Abstract Induced polarization (IP) measurements in porous sedimentary rocks are modeled in terms of pore geometrical descriptors (PGD). Using an extensive data set composed of 241 sandstone, carbonate, and arenite samples, we identified a stronger relationship between IP parameters and volumetric magnetic susceptibility versus IP parameters and PGD. This finding suggests that even small concentrations of iron minerals in rocks typically thought to lack electron-conducting minerals can significantly influence IP measurements. The combination of magnetic susceptibility with a pore geometrical descriptor term improves the empirical prediction of IP measurements relative to the use of pore geometrical descriptor terms alone. This suggests that small concentrations of iron minerals exert a strong control on the specific capacitance, a property that remains poorly understood. The lack of any relationship between magnetic susceptibility and the PGD confirms that the magnetic susceptibility provides additional information unrelated to PGD.

Plain Language Summary Geophysical measurements such as induced polarization (IP) provide essential information about the properties that control the flow and transport of fluids, including groundwater and contaminants, in the subsurface. Understanding such subsurface processes is critical to efforts to promote environmental sustainability and stewardship. IP measurements are thought to be primarily controlled by the geometry of the interconnecting pores of sedimentary rocks, as quantified by parameters such as the surface area or grain size. Such sedimentary rocks are usually assumed to be devoid of electron-conducting minerals. By measuring a simple property known as the magnetic susceptibility, we find that low concentrations of magnetic minerals in these sedimentary rocks influence IP measurements just as much, if not more than, the pore geometrical descriptor terms that appear in empirical and physical models for IP. This finding suggests that models describing the IP signatures in sedimentary rocks need to consider mineralogy.

1. Introduction

Induced polarization (IP) is a non-invasive geophysical technique used for sensing variations of pore geometrical properties that control fluid flow and transport in sedimentary rocks devoid of a significant concentration of electron conducting minerals. Experimental work on sedimentary rocks and unconsolidated sediments has shown that pore geometrical descriptors (PGD) are a primary factor controlling IP measurements in these porous materials. PGD terms such as the surface area normalized to pore volume \( S_{\text{por}} \) are used in both mechanistic (Leroy et al., 2008; Revil, 2012, 2013; Weller & Slater, 2012) and empirical models (Börner et al., 1996; Weller et al., 2010, 2011, 2013; Weller & Slater, 2015) for IP prediction. This IP dependence on PGD (IP-\( S_{\text{por}} \)) improves, particularly for samples with low permeability, when the effect of the formation factor is included to account for the volume and tortuosity of the interconnected pore network (Niu et al., 2016). However, factors influencing IP unrelated to PGD but controlled by the surface electrochemistry and particle mineralogy are less understood.

This study reports on an extensive database of porous sedimentary rock samples that would be expected to have IP characteristics controlled by the PGD. While our results reflect previous findings on the importance of PGD terms, they also highlight the importance of variations in the specific capacitance due to variations in particle mineralogy.

A measure of magnetic susceptibility (\( \kappa \)) is commonly used to detect traces of iron minerals. We show that magnetic susceptibility measurements exhibit a surprisingly strong correlation with IP parameters, being at least equal to the role of the PGD term. This new finding has implications for defining what controls the specific...
capacitance of the pore surface-fluid interface and ultimately improving the understanding of petrophysics for IP in sedimentary rocks and unconsolidated sediments.

1.1. Electrical Properties of Rocks

In porous media, and in the absence of electronic conduction, charge transport occurs by conduction through dissolved ions in the pore fluid filling the spaces of interconnected pores and conduction through ions in the electrical double-layer (EDL) at the mineral-fluid interface. These mechanisms give rise to the electrolytic conductivity ($\sigma_{el}$) and surface conductivity ($\sigma_{surf}$) of a porous medium respectively. They are commonly modeled to act in parallel (Lesmes & Frye, 2001; Waxman & Smits, 1968) so that the total conductivity of a porous medium can be described as,

$$\sigma = \sigma_{el} + \sigma_{surf}.$$  

(1)

Given that most matrix forming minerals in porous sedimentary media are electrical insulators, the conductivity of the porous medium is reduced in relation to the conductivity of the surrounding pore saturating fluid ($\sigma_w$). This reduction in conductivity is described by the formation factor (Archie, 1942),

$$F = \frac{\sigma_w}{\sigma_{el}} = \phi^{-m}.$$  

(2)

where $m$ is the cementation exponent and $\phi_{int}$ is the interconnected porosity. In general, the surface conductivity is a complex term ($\sigma^*$), as both conduction and temporary, reversible storage of charge occurs in the EDL, such that,

$$\sigma^* = \sigma' + i\sigma'' = \sigma_{el} + \sigma'_{surf} + i\sigma''_{surf}.$$  

(3)

where $\sigma^*$ is the measured complex conductivity, and single prime and double prime superscripts represent real and imaginary conductivity components respectively (Lesmes & Frye, 2001; Vinegar & Waxman, 1984). The real conductivity represents conduction strength (electromigration) in the interconnected pore network and adjacent EDL, while the imaginary conductivity signifies the polarization strength (i.e., the reversible temporary charge) occurring in the EDL,

$$\sigma' = \sigma_{el} + \sigma'_{surf},$$  

(4)

$$\sigma'' = \sigma''_{surf}.$$  

(5)

In general, the complex conductivity terms are frequency dependent, and therefore are measured using the spectral induced polarization (SIP) method, the frequency-dependent form of IP. SIP measurements are typically preformed within a frequency range of 1 mHz to 1 kHz.

The EDL polarization, being a diffusion-controlled redistribution of charges predominantly tangential to the mineral surfaces, is foremost controlled by PGD (e.g., grain and pore-size distribution, texture) of the porous medium (Börner, 1992; Börner & Schön, 1991; Leroy et al., 2008; Niu et al., 2016; Revil et al., 2014; Slater & Lesmes, 2002). This diffusive EDL polarization is primarily observed at relatively low frequencies ($<10^3$ Hz). At higher frequencies ($>10^3$ Hz) the Maxwell-Wagner polarization mechanism, where polarization in a porous medium originates from the discontinuity in conductivity at interfaces between different states of matter, may dominate (de Lima & Sharma, 1992).

1.2. IP Measurements

In this paper, we focus on the polarization strength from two (IP) parameters—the first being $\sigma''$ at a frequency of 1 Hz, and the second being normalized chargeability ($m_n$), the polarization magnitude determined from a number of individually computed Debye relaxation times throughout a fixed-frequency range (Nordsiek & Weller, 2008; Ustra et al., 2016).

The influence of PGD on these measures of polarization strength has been demonstrated through empirical observations. For example, the dependence of these parameters on pore-volume normalized specific surface area ($S_{por}$)
has been demonstrated on a database consisting of sandstones and unconsolidated sedimentary samples (Börner et al., 1996; Weller et al., 2010; Weller & Slater, 2015). Weller et al. (2010) approximate this relationship between polarization magnitude (IP parameters) and $S_{\text{por}}$ as,

$$\sigma''_{1Hz} = c_p S_{\text{por}},$$

(6)

$$m_s = c_s S_{\text{por}},$$

(7)

The slope variable ($c_p$ or $c_s$) is defined as the specific polarizability (Weller et al., 2011), being the polarization per unit $S_{\text{por}}$, which is assumed to reflect the dependence of the polarization on both particle mineralogy and surface electrochemistry (Weller et al., 2010, 2011). Niu et al. (2016) revisit the linear approximation in the IP-$S_{\text{por}}$ relation and include the formation factor $F$,

$$\sigma''_{1Hz} = c_p F S_{\text{por}},$$

(8)

$$m_s = c_s F S_{\text{por}},$$

(9)

thereby recognizing the importance of porosity and tortuosity (accounted for by $F$) of the EDL, particularly in samples with low porosity.

However, significant scattering of data points is evident in the previously investigated IP-$S_{\text{por}}$ empirical models with and without the consideration of $F$. Weller et al. (2010) presented measurements on synthetic clay-sand mixtures and iron-sand mixtures to provide evidence for a mineralogical control on the specific polarizability. In this paper, we explore evidence of this mineralogical control on IP measurements in a range of sedimentary rocks from measurements of magnetic susceptibility.

2. Materials and Methods

Our database contains 241 porous sedimentary rock-core samples composed of predominately sandstone, carbonate, and arenite lithology. Included in this data set are 24 Eocene sandstone samples of the Shahejie formation from the Chinese Henan Province (Zhang & Weller, 2014), 38 Late-Cretaceous carbonates from the Tushka area of the Egyptian Western desert (Halisch et al., 2014), 40 Upper-Cretaceous sandstones of the Bahariya formation from the Egyptian Western Desert (Abuseda et al., 2016), 21 Cretaceous sandstones from California (USA) (Robinson et al., 2018), and 21 Cambrian-Ordovician sandstones from Wisconsin (USA) (Robinson et al., 2018). The remaining 97 samples, which include 64 carbonate samples, 14 arenite samples, and 19 sandstone samples from the Red Sea, are previously unpublished.

We briefly report on the procedures used to obtain the sample parameters for 139 of the 241 samples included in the database. Procedures to determine sample parameters from the Shahejie, Tushka, and Bahariya sandstones differ only slightly and are reported in the original publications (Abuseda et al., 2016; Halisch et al., 2014; Zhang & Weller, 2014). The mass-related specific-surface-area $S_m$ was determined from nitrogen gas adsorption measurements (Brunauer et al., 1938) and $S_{\text{por}}$ was calculated from,

$$S_{\text{por}} = \rho_i \frac{(1 - \phi)}{\phi} S_m,$$

(10)

where $\rho_i$ is the particle density and $\phi$ is the total porosity. $S_{\text{por}}$ was calculated in two trials, with an average relative error of 4.4%. Volumetric magnetic susceptibility ($\kappa$) was recorded as an average of four measurements (two on the flat side of each core sample) to account for heterogeneity, with an average relative error of 2.4%. Measurements were collected using a handheld portable sensor manufactured by Bartington Instruments (UK).

To enable IP measurements, cores were saturated in two stages using a custom-built high-pressure chamber. In the first stage, a low-conductivity (100 mSm) fluid was used to be representative of groundwater and to facilitate comparisons with previous studies. Cores were sealed in a stainless-steel chamber and vacuumed until a pressure threshold of 1.45$^{-3}$ psi. The vacuumed chamber was then invaded with the synthetic groundwater solution. Samples were pressurized at 2,000 psi for approximately 3 days to ensure adequate saturation of pores. Saturated
cores were then placed into sample holders containing a pair of silver-silver-chloride (Ag-AgCl) current coil electrodes and a pair of Ag-AgCl point potential electrodes. The metal part of the potential electrodes was recessed from the sample edge in fluid-filled chambers to prevent spurious electrode polarization errors. Cores were placed inside an environmental chamber and SIP measurements were recorded (two measurements per core to test for repeatability) over the frequency range of 0.01 Hz–10 kHz at a constant temperature of 25°C. After measurements were completed, cores were oven dried at 80°C to prepare for the second saturation stage, where the procedure was repeated using a high-salinity solution (σw ≈ 8000 mS/m) thereby minimizing the contribution of σsurf to σc, permitting estimation of the formation factor from Equation 2. We measured an average relative error of 1.57% for low-conductivity IP data and 2.9% for F (specific errors are reported in the Data Set S1).

Complex impedance measurements were acquired using a portable spectral induced polarization (PSIP) instrument manufactured by Ontash & Ermac (New Jersey, USA). Conversion of complex impedance to σc was achieved using the geometric factor for each sample that was determined by filling the sample holders with three fluids of known electrical conductivity, varying over two orders of magnitude (e.g., σw = 10, 100, and 1,000 mS/m). The geometric factor was estimated from the linear coefficient in the regression of 1/σw versus the resistance.

Calculated values of σ" were corrected to an equivalent fluid conductivity of 100 mS/m using the approach of Weller et al. (2011) to minimize the weak effect of the fluid conductivity on the polarization strength over this limited σw range.

The Debye-decomposition (DD) method (Nordsiek and Weller, 2008; Ustra et al., 2016) was used to determine the polarization magnitude over the frequency range 0.01–100 Hz. This approach determines a distribution of relaxation times (each time related to a characteristic length scale of the polarization via a diffusion coefficient) along with two frequency-independent parameters (total chargeability m0 and DC resistivity ρ0) to model the measured complex conductivity spectra. The overall polarization strength between the selected minimum (0.01 Hz) and maximum (100 Hz) spectra range (referred to as normalized chargeability m) was calculated from the inverted parameters by,

\[
m = \frac{m_0}{\rho_0}\n\]

3. Results

The dependence of the IP parameters (σ"1Hz and m) on PGD properties (Sp0 and Sp0 \( F^{-1} \)) is first described here. PGD parameters Sp0 and Sp0 \( F^{-1} \) are reported in units of \( \mu \text{m}^{-1} \) and polarization parameters as mS/m. The dependence of the polarization parameters (IP) on \( \kappa \) is subsequently analyzed. Thereafter, the benefit of combining \( \kappa \) with a PGD term for describing the polarization magnitude of sedimentary rocks is explored.

In all the following plots, open symbols in the figures represent sandstone mineralogy and closed symbols represent carbonate or dolomite mineralogy. The coefficient of determination (R2) is included for all samples, carbonates only, and sandstones only, to explore the level of variance between the sample types. The Akaike information criterion (AIC) is reported to evaluate to what degree the increase in the goodness of fit of the empirical models is simply due to increasing the number of model variables rather than representing a better-quality model (a lower or more negative AIC value indicates a higher quality model) (Akaike, 1987). An increase in the number of variables that results in a similar or slightly more negative AIC still suggests model improvement. The standardized mean difference method (Cohen’s d) of Cohen (2013) is applied to assess deviations from predicted and measured IP values, with a lower d-value indicating a better fit.

3.1. The IP-\( S_{\text{por}} \) Relationship

The relationships between the IP parameters (σ"1Hz and m) and Sp0 are displayed in Figure 1a and Figure 1b respectively. The red line represents the linear relationship for 114 sandstone, clay-sandstone and unconsolidated samples reported in Weller et al. (2010). Heavy data point scattering is apparent for both polarization parameters (σ"1Hz and m). The poor linear correlation with \( S_{\text{por}} \) observed for both σ"1Hz and m (R2 = 0.019 for all samples, 0.24 for carbonates only, and 0.066 for sandstones only in Figure 1a, and 0.011 for all samples, 0.27 for carbonates only, and 0.064 for sandstones only in Figure 1b) suggests that the control of \( S_{\text{por}} \) on IP is not strong when considering a large data set composed of a diverse group of samples with varying porosity and mineralogy.
In the predicted relationship, where $A_p$ and $A_s$ are optimized, $d = 0.78$ for all samples, $0.33$ for carbonates only ($A_p = 0.0006$), and $0.65$ for sandstones only ($A_p = 0.0021$) for $A_p^{\prime \prime \text{pred}}$, and $0.61$ for all samples, $0.32$ for carbonates only ($A_s = 0.0036$), and $0.65$ for sandstones only ($A_s = 0.0156$) for $A_s^{\text{pred}}$.

3.2. The IP-$S_{\text{por}} F^{-1}$ Relationship

Figures 1c and 1d show the effects of incorporating the formation factor ($F$) into the IP-$S_{\text{por}}$ relations (Equations 8 and 9). Consistent with other studies (Niu et al., 2016; Weller & Slater, 2012), the use of $S_{\text{por}} F^{-1}$ results in a
stronger relationship with IP parameters relative to $\sigma''$ alone. $R^2$ increases from 0.019 to 0.37 for all samples (0.24 to 0.41 for carbonates only and 0.066 to 0.37 for sandstones only) in the relationship $\sigma''_{\text{IP}} = c_\sigma(S_{\text{pgd}} F^{-1})$, and from 0.011 to 0.38 for all samples (0.27 to 0.35 for carbonates only and 0.064 to 0.4 for sandstones only) in the relationship $m_a = c_\sigma(S_{\text{pgd}} F^{-1})$. Cohen's $d$ is 0.43 for all samples, 0.41 for carbonates only ($c_\sigma = 0.0348$), and 0.57 for sandstones only ($c_\sigma = 0.0635$) for $\sigma''_{\text{IP}}$ and $0.42$ for all samples, 0.48 for carbonates only ($c_\sigma = 0.184$), and 0.55 for sandstones only ($c_\sigma = 0.492$) for $m_a$. Although the improvement is significant, extensive scatter around the relation is still evident in the data.

3.3. The IP-$\kappa$ Relationship

Unlike the case of the PGD relation, there is currently no theoretical basis for a relationship between IP and $\kappa$. We therefore explore both linear and power-law relationships. The linear IP-$\kappa$ relation is defined as,

$$\sigma''_{\text{IP}} = a_m(\kappa),$$

$$m_a = a_0(\kappa),$$

with the variables $a_m$ and $a_0$ indicating the slope of the regression. Figure 2 shows that the linear IP-$\kappa$ relation ($R^2 = 0.48$ for all samples, 0.59 for carbonates only, and 0.47 for sandstones only for $\sigma''_{\text{IP}}$, and 0.5 for all samples, 0.66 for carbonates only, and 0.5 for sandstones only for $m_a$) is similar, in fact arguably slightly better (based on higher $R^2$ and lower $d$-values) to the IP dependence on PGD (max $R^2 = 0.38$) shown in Figure 1.

The power-law IP-$\kappa$ relation is defined as,

$$\sigma''_{\text{IP}} = a_{mb}(\kappa)^b,$$

$$m_a = a_{0b}(\kappa)^b,$$

with variables $a_{mb}$ and $a_{0b}$ representing the slope of the best-fit line and $b$ signifying the power-law exponent. An AIC of $-10.3$ and a $R^2 = 0.59$ for the power-law $\sigma''$-$\kappa$ relation (Figure 2a) indicates a higher quality model.
3.4. Combining $\kappa$ and $S_{\text{por}}F^{-1}$ Into an IP Relation

We modify the IP-$S_{\text{por}}F^{-1}$ relation in Equations 8 and 9 by combining PGD with $\kappa$, transforming the relationships to,

$$\sigma''_{\text{pred}} = a_{\sigma''}k^b\left(\frac{S_{\text{por}}}{F}\right)^c,$$

$$m_{\sigma'\text{pred}} = a_{m\kappa}k^b\left(\frac{S_{\text{por}}}{F}\right)^c.$$

We assume a power law dependence on $\kappa$ as the theoretical relationship between $\kappa$ and IP is unknown. The predicted IP parameters ($\sigma''_{\text{pred}}$ and $m_{\sigma'\text{pred}}$), based on non-linear regression to find optimal values of the coefficients $a_{\sigma''}, a_m, a_{m\kappa}$, and $b$, are plotted as a function of measured IP parameters ($\sigma''_{\text{pred}}$ and $m_{\sigma'\text{pred}}$) in Figure 3. An identity line (1:1 line) is included to assess data point scattering using the predicted and measured values.

Figures 3a and 3b show that combining $\kappa$ and PGD using Equations 16 and 17 results in a substantially improved correlation for both IP parameters ($\sigma''_{\text{pred}}$ and $m_{\sigma'\text{pred}}$) compared to only using PGD (Figure 1) or $\kappa$ (Figure 2) alone. The scattering observed in Figure 1 is significantly reduced in Figure 3, as evident by data points collapsing toward the identity line (1:1 line). The AIC decreases from $-6.54$ (Figure 1c) to $-9.92$ (Figure 3a), indicating that this improvement is not just a consequence of adding an extra parameter. The relationship improves, even more so, when carbonate and sandstone groups are separated. The standardized mean difference decreases to 0.26 for carbonates only ($a_{\text{pm}} = 1.83, b = 0.29$) and 0.31 for sandstones only ($a_{\text{pm}} = 0.29, b = 0.018$) for the case of $\sigma''_{\text{pred}}$, and 0.27 for carbonates only ($a_{\text{sm}} = 51.1, b = 0.41$) and 0.31 for sandstones only ($a_{\text{sm}} = 1.72, b = 0.001$) for the case of $m_{\sigma'\text{pred}}$.

Finally, although theory indicates a linear relationship between IP parameters and $S_{\text{por}}F^{-1}$, we relax this constraint by applying an additional free parameter $c$ to the PGD ($S_{\text{por}}F^{-1}$) to evaluate the degree of improvement for a purely empirical form,

$$\sigma''_{\text{pred}} = ak^b\left(\frac{S_{\text{por}}}{F}\right)^c,$$

$$m_{\sigma'\text{pred}} = ak^b\left(\frac{S_{\text{por}}}{F}\right)^c.$$

The standardized mean difference further decreases to $d = 0.24$ for all samples, 0.22 for carbonates only ($a = 1.06, b = 0.3, c = 0.58$), and 0.25 for sandstones only ($a = 0.66, b = 0.17, c = 0.55$) for the case of $\sigma''_{\text{pred}}$, and 0.25 for all samples, 0.23 for carbonates only ($a = 136.9, b = 0.57, c = 0.55$), and 0.26 for sandstones only ($a = 1.08, b = 0.005, c = 0.51$) for the case of $m_{\sigma'\text{pred}}$. After applying this modification, the AIC decreases from $-9.92$ (Figure 3a) to $-13.9$ (Figure 3c) for $\sigma''_{\text{pred}}$, suggesting that this adjustment produces a higher quality model. However, the AIC remains relatively similar in the case of $m_{\sigma'\text{pred}}$ between linear and power law forms of the PGD term (Figures 3b and 3d).

A plot of $\kappa$ as a function of PGD terms ($S_{\text{por}}$ and $S_{\text{por}}F^{-1}$) in Figure 4 confirms that there is no significant relationship between these parameters ($R^2 = 0.09$ for all samples, 0.14 for carbonates only, and 0.2 for sandstones only for $S_{\text{por}}$, and 0.14 for all samples, 0.054 for carbonates only, and 0.11 for sandstones only for $S_{\text{por}}F^{-1}$). This confirms that $\kappa$ is providing independent information from the PGD terms to the prediction of IP parameters for these samples.

4. Discussion

The relationships observed between IP measures and $\kappa$ are as significant, if not stronger, than the relationships between IP measures and PGD terms ($S_{\text{por}}$ and $S_{\text{por}}F^{-1}$) reported in previous research on sedimentary rocks. This
finding suggests that the specific capacitance appearing in the IP versus PGD relation is partly controlled by mineralogical differences associated with low concentrations of iron-bearing minerals. Moreover, the stronger improvement observed when separating carbonate and sandstone rock samples versus combining them may suggest that the parameter $\kappa$ compensates for internal and external Fe or Fe-oxide within the varying rock matrix lithologies. As far as we are aware, Chen et al. (2021) is the only other study reporting any relationship between IP measures (in their case the time domain chargeability) and $\kappa$, but for the unique case of serpentinized mid-ocean volcanic rocks with high magnetite concentrations.
Regarding PGD, exploration of this database confirms that $S_{por} F^{-1}$ is the appropriate geometric parameter, rather than $S_{por}$, when considering a wide range of sample lithologies. Consistent with other studies, carbonate and dolostone samples fall significantly below the relationship identified in Weller et al. (2010). Sandstone samples plot reasonably close to the line of equality (1:1 line) previously defined for the sandstone and unconsolidated sediments by Weller et al. (2010). The incorporation of formation factor $F$ into the $S_{por}$ relation highlights the importance of tortuosity in rock samples characterized by high formation factor and low porosity (evident with carbonate samples falling closer to the 1:1 line when $S_{por}$ is included). The linear dependence of IP measures on $S_{por} F^{-1}$ matches theoretical assumptions proposed in diffuse layer (Rink & Schopper, 1974; Weller & Slater, 2012) and Stern layer (Leroy et al., 2008; Weller & Slater, 2012) models. Niu et al. (2016) develop a general theoretical relationship between $\sigma''$ and PGD that also predicts a linear dependence of $\sigma''$ on $S_{por} F^{-1}$.

The observed dependence of IP measures on $\kappa$ suggests that small concentrations of electron-conducting or semi-conducting minerals exert a significant control on IP in porous rocks that would usually be considered devoid of significant concentrations of such minerals. The strong dependence of IP on significant concentrations (parts per hundred or more) of electron conducting minerals is well known in the mineral exploration community, where IP was first developed for detecting disseminated mineral deposits. However, it is traditionally assumed that the mechanisms responsible for the relatively small IP effect in non-electron conducting rocks, such as the sedimentary rocks explored in this study, are fundamentally different from those in rocks where the presence of significant (1% or more) concentrations of conductive minerals dominate the IP effect relative to the polarization of the background matrix (the background polarization defined by Schlumberger (1920)). However, Weller et al. (2010) showed that the specific capacitance changes when significant fractions of iron minerals are added to synthetic sand mixtures. These findings imply that describing IP in terms of PGD parameters alone is insufficient when dealing with sedimentary rocks and unconsolidated sediments. Including both a mineralogy control, here represented by the $\kappa$ term, and a PGD control, will instead be necessary to accurately predict the IP signature of sedimentary rocks and unconsolidated sediments.

5. Conclusions

Using an extensive database of 241 samples, we have presented a new perspective on the dominant controls on IP in sedimentary rocks. Beyond PGD, the magnetic susceptibility ($\kappa$), presumably controlled by small

Figure 4. Cross plots of magnetic susceptibility $\kappa$ and PGD terms for 241 sedimentary samples (sandstone, carbonate, and arenite): (a) $S_{por}$ and (b) $S_{por} F^{-1}$. Open symbols represent sandstone mineralogy, closed symbols represent carbonate/dolomite mineralogy, and arenite is represented by “x”.

 SEN (Dolostone) ▲ Tushka (Carbonate microfacies 1)
 DAV (Dolostone) ▲ Tushka (Carbonate microfacies 2)
 × Araba (Arenite) ▶ MB (Karstic Limestone/Dolostone)
 ◯ HC (Sandstone) ▲ Shahejje (Sandstone)
 □ C3 (Sandstone) ◀ Bahariya (Sandstone)
 ○ RD (Sandstone) ▲ Red Sea (Sandstone)
concentrations of iron-minerals, is shown to significantly influence IP measurements in rocks that would usually be considered devoid of electron-conducting particles. \( \kappa \) is not significantly correlated with the PGD terms. Combining \( \kappa \) with the PGD term \( S_{\text{PGD}} F^{-1} \) results in an improvement in a predictive equation for estimating IP parameters (\( \sigma''_{11c} \) and \( m_c \)). Our results suggest that \( \kappa \), and thus iron mineralogy, exerts a significant control on the specific capacitance appearing in the IP-PGD relation for sedimentary rocks. Our results also reinforce previous findings that \( S_{\text{PGD}} F^{-1} \) is the appropriate expression for describing the role of the PGD on IP measurements when considering a wide range of lithologies that include low porosity samples with high formation factors.

Data Availability Statement

All data used in this study are publicly available from the Hydroshare archive using the following link: https://www.hydroshare.org/resource/f50547502b6a4f6d824adb11192f56df/. Complete raw SIP spectra for the many of the previously published samples are accessible via the SIP community repository SIP-Archiv.

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