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Petrophysical properties of mineralized and nonmineralized rocks from Giant and Con mine areas, Northwest Territories[1]

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Abstract: Petrophysical measurements, including electrical resistivity, effective porosity, and bulk density, have been performed on ten mineralized and nonmineralized rock samples from the Giant mine and Con mine areas (Northwest Territories). The purpose was to determine the petrophysical characteristics of these rocks and provide information required to determine their electrical conductivity mechanism and to aid interpretation of down-hole, ground, and airborne electromagnetic survey data.

Results indicate that bulk densities (δ_B) are in the range of 2.86–3.13 g/mL. Effective porosities (ϕ_E) range from 0.40% to 3.03%, with the ϕ_E values for samples from the Con mine area being generally smaller (0.40–1.16%) than those from the Giant mine area (0.42–3.13%). Bulk electrical resistivities (ρ_r) are in the range of 37–2.4 x 10^4 Ω·m, for these samples. The moderately to strongly foliated texture of these samples result in electrical resistivity anisotropy values of 2:1 to 46:1.

Résumé : Des mesures pétrophysiques, incluant des mesures de la résistivité électrique, de la porosité efficace et de la masse volumique apparente, ont été effectuées pour 10 échantillons de roches minéralisées et non minéralisées provenant des mines Con et Giant à Yellowknife (Territoires du Nord-Ouest). Ces mesures avaient pour objets de déterminer les caractéristiques pétrophysiques de ces roches et d'obtenir l'information nécessaire pour déterminer le mécanisme de leur conductivité électrique afin de faciliter l'interprétation des données de levés électromagnétiques de sondage, au sol et aériens.

Les résultats indiquent que la masse volumique apparente (δ_B) varie de 2,86 à 3,13 g/mL et la porosité efficace (ϕ_E), de 0,40 à 3,03%; les valeurs de ϕ_E pour les échantillons provenant de la mine Con étaient généralement plus faibles (de 0,40 à 1,16 %) que celles obtenues avec les échantillons provenant de la mine Giant (de 0,42 à 3,13 %). La résistivité électrique apparente (ρ_r) de ces échantillons varie de 37 x 10^4 Ω·m à 2,4 x 10^4 Ω·m. La texture modérément à fortement feuilletée de ces échantillons leur confère des valeurs de l'anisotropie de la résistivité électrique variant de 2:1 à 46:1.

[1] Contribution to the 1999-2003 Yellowknife, Canada-Northwest Territories Exploration Science and Technology (EXTECH III) Initiative

INTRODUCTION

A set of petrophysical measurements, including electrical resistivity, effective porosity, and bulk density, have been performed on a suite of ten mineralized and nonmineralized rock samples from the Giant mine and Con mine areas, Northwest Territories. The purpose was to provide basic data to be used in determining the petrophysical characteristics and electrical conductivity mechanism of these rocks, which would provide information required to develop exploration strategies for aiding interpretation of down-hole, ground, and airborne electromagnetic surveys. The samples include material from gold-bearing quartz veins; sericite schist and chlorite schist from sheared zones that run parallel to the vein; and basalt that constitutes the host rock. This paper describes the methods and processes used to obtain the petrophysical data, and documents the results in as much detail as considered necessary for subsequent studies that would use the data.

METHOD OF INVESTIGATION

Samples and sample preparation

The ten samples used in this study were selected from a set of 34 hand samples, collected underground by Jonathan Mwenifumbo and John Kerswill, from the Giant and Con mines, Yellowknife, Northwest Territories. Five samples are from the Giant mine and five are from the Con mine. Information on sample location and lithology is listed in Table 1.

Usually, more than one specimen was cut from each sample into rectangular shapes with their edges either parallel or perpendicular to foliation. At least one specimen from each sample was used for determination of bulk density, δ_B, and bulk electrical resistivity, ρ_r, and one for determination of effective porosity, ϕ_E, whenever possible. In some cases, several rectangular specimens were cut from a sample, to be used for the ρ_r measurements, so that different components of the heterogeneities and anisotropy of the rock could be characterized. If, for example, the sample number was MYC-2, then these specimens would be labelled MYC-2a, MYC-2b, and MYC-2c. Samples with high sulphide content were avoided only for the porosity determination, due to concern over their possible oxidation under moist conditions at elevated temperatures (100°C). The geometric characteristics of the specimens used for the 3-D ρ_r and δ_B measurements are listed in Table 2. Some of the rectangular specimens prepared for the ρ_r measurements are used for scanning electron microscope analyses (Connell et al., 2000), to examine the sample texture and fabric, including the connectivity of the sulphide mineral grains.

Table 1. Rock descriptions and location for samples collected from the Giant and Con mines (Yellowknife, Northwest Territories).

Mine	Sample number	Stopes sampled	Lithology
Giant	MYG-8	370	Chlorite schist
	MYG-9	370	Ore
	MYG-11	370	Sericite schist
	MYG-13	370	Sericite schist
	MYQ-1	Surface	Basalt
Con	MYC-1	3148R	Sericite schist
	MYC-2	3148R	Chlorite-sericite schist
	MYC-6	3148R	Basalt
	MYC-7	3196R	Chlorite schist
	MYC-11	3322AY	Ore

Bulk-density and effective-porosity measurements

The caliper method (American Petroleum Institute, 1960) has been used to determine the bulk density (δ_B) of the samples, by measuring the dimensions and weight of the rectangular specimens. This measurement constitutes part of the porosity-determining procedure. Effective porosity (ϕ_E) in principle represents the pore volume of all interconnected pores. In this study, it is determined from the difference in weight between the oven-dried and water-saturated rock specimen. The American Petroleum Institute Recommended Practice

Table 2. Dimensions of specimens cut out from the samples for electrical resistivity measurements.

Sample /Ms-Dir	a_1 (cm)	a_2 (cm)	ℓ (cm)	W (g)	V (cm^3)	K_G (10^{-2} m)	δ_B (g/mL)
MYC-1α	1.826	2.185	1.075	12.8337	4.29	3.71	2.99
MYC-1β	1.075	2.185	1.826	12.8337	4.29	1.29	2.99
MYC-1γ	1.075	1.826	2.185	12.8337	4.29	0.898	2.99
MYC-2aα	1.883	2.126	1.176	14.2047	4.71	3.4	3.02
MYC-2aβ	1.176	2.126	1.883	14.2047	4.71	1.33	3.02
MYC-2aγ	1.176	1.883	2.126	14.2047	4.71	1.04	3.02
MYC-2bα	0.904	1.682	0.968	4.4954	1.47	1.57	3.05
MYC-2bβ	0.968	1.682	0.904	4.4954	1.47	1.8	3.05
MYC-2bγ	0.904	0.968	1.682	4.4954	1.47	0.52	3.05
MYC-6α	1.403	2.106	0.904	8.0624	2.67	3.27	3.02
MYC–6β	0.904	2.106	1.403	8.0624	2.67	1.36	3.02
MYC–6γ	0.904	1.403	2.106	8.0624	2.67	0.602	3.02
MYC-7α	1.783	2.016	1.245	13.0537	4.48	2.89	2.92
MYC-7β	1.245	2.016	1.783	13.0537	4.48	1.41	2.92
MYC-7γ	1.245	1.783	2.016	13.0537	4.48	1.1	2.92
MYC-11α	1.377	1.533	1.157	7.6204	2.44	1.82	3.12
MYC-11β	1.157	1.533	1.377	7.6204	2.44	1.29	3.12
MYC-11γ	1.157	1.377	1.533	7.6204	2.44	1.04	3.12
MYQ-1α	1.548	2.168	1.099	11.5615	3.69	3.05	3.13
MYQ-1β	1.099	2.168	1.548	11.5615	3.69	1.54	3.13
MYQ-1γ	1.099	1.548	2.168	11.5615	3.69	0.785	3.13
MYG-8α	2.253	2.197	1.498	21.1845	7.41	3.3	2.86
MYG-8β	1.498	2.253	2.197	21.1845	7.41	1.54	2.86
MYG-8γ	1.498	2.197	2.253	21.1845	7.41	1.46	2.86
MYG-9α	2.161	2.233	2.098	31.5782	10.12	2.3	3.12
MYG-9β	2.098	2.233	2.161	31.5782	10.12	2.17	3.12
MYG-9γ	2.098	2.161	2.233	31.5782	10.12	2.03	3.12
MYG-11aα	2.141	2.17	1.51	21.3302	7.02	3.08	3.04
MYG-11aβ	1.51	2.141	2.17	21.3302	7.02	1.49	3.04
MYG-11aγ	1.51	2.17	2.141	21.3302	7.02	1.53	3.04
MYG-11bα	1.451	1.983	1.334	11.1837	3.84	2.16	2.91
MYG-11bβ	1.334	1.983	1.451	11.1837	3.84	1.82	2.91
MYG-11bγ	1.334	1.451	1.983	11.1837	3.84	0.976	2.91
MYG-13α	1.411	1.752	1.403	10.585	3.47	1.76	3.05
MYG-13β	1.403	1.752	1.411	10.585	3.47	1.74	3.05
MYG-13γ	1.403	1.411	1.752	10.585	3.47	1.13	3.05

Ms-Dir = Direction of measurement: α, β, γ
a_1, a_2 = Length of the two sides of the rectangular specimen
ℓ = Thickness of specimen
W = Weight of specimen under room dry conditions
K_G = Geometric factor
δ_B = Bulk density

for Core-Analysis Procedures (American Petroleum Institute, 1960) has generally been followed in these measurements. The procedures routinely used in our measurements are described in the literature (Katsube and Scromeda, 1991; Katsube et al., 1992; Scromeda and Katsube, 1994).

Bulk electrical resistivity measurements

The bulk electrical resistivity (ρ_r) is determined from the complex electrical resistivity, ρ^*, method described in recent publications (e.g. Katsube et al., 1991; Katsube and Salisbury, 1991; Katsube and Scromeda, 1994). The complex electrical resistivity (ρ^*) is measured over a frequency range of 1–10^6 Hz, with ρ_r representing a bulk electrical resistivity at frequencies of about 10^2–10^3 Hz. It is a function of the pore structure and pore fluid resistivity, and is understood to exclude effects, such as pore surface, dielectric, or other polarizations including electrode polarization (Katsube, 1975; Katsube and Walsh, 1987). Further details of the analytical procedure are described elsewhere (e.g. Katsube and Scromeda, 1994; Katsube et al., 1996).

Table 3. Results of density and the effective porosity measurements.

Sample	δ_B (g/mL)	W_W (g)	W_D (g)	S_{ir} (%)	ϕ_E (%)
MYC-1	2.99	7.4256	7.3968	17.4	1.16
MYC-2	3.02	3.7704	3.7604	25.0	0.80
MYC-6	3.02	7.6343	7.6242	47.5	0.40
MYC-7	2.92	4.6775	4.6688	23.0	0.54
MYC-11	3.12	8.2695	8.2546	51.0	0.56
MYQ-1	3.13	5.6678	5.6603	24.0	0.42
MYG-8	2.86	10.5665	10.4559	3.8	3.03
MYG-9	3.12	6.6968	6.6426	10.5	2.55
MYG-11A	3.04	6.4352	6.3938	9.4	1.97
MYG-11B	2.91	4.2230	4.1819	5.8	2.86
MYG-13	3.05	2.4185	2.4070	27.8	1.46

δ_B = Bulk density
W_w = Wet weight
W_D = Dry weight
S_{ir} = Irreducible water saturation
ϕ_E = Effective porosity

EXPERIMENTAL RESULTS

The results of the bulk density (δ_B) determinations are listed in Table 2, and the δ_B values are in the range of 2.86–3.13 g/mL. The results of the effective porosity (ϕ_E) measurements are listed in Table 3 for samples visibly barren of sulphide minerals, displaying ϕ_E values in the range of 0.40–3.03%.

The results of the bulk electrical resistivity (ρ_r) measurements are listed in Table 4. Determinations have been made at 24 and 48 hours after water saturation, to ensure that they represent ρ_r values stable with time. Under this state, it is expected that the deionized water has chemically equilibrated with the rock, and represents the in situ condition. Normally, differences up to ±20% of their mean are considered to be within measurement error and represent stable conditions. In the present study, many of the samples from the Con mine exceed that value (e.g. sample MYC-1, MYC-6, MYC-11). Thirty-six measurements (including three-directional measurements) were made for 12 specimens, representing 10 samples.

Typical examples of complex resistivity (ρ^*) plots; ρ^* as a function of frequency, f; ρ_I as a function of ρ_R; and imaginary conductivity (σ_I) as a function of real conductivity (σ_R); used to determine ρ_r values are shown in Figures 1–4. These figures display various complex resistivity arc patterns. Examples of complex resistivity data, including real (ρ_R) and imaginary (ρ_I) electrical resistivity data used for these plots over a frequency range of 1–10^6 Hz, are listed for six typical samples in Tables 5a, 5b, and 5c.

Table 4. Results of electrical resistivity measurements.

Sample	Lithology	Mean ρ_r, (10^3 Ω·m) α	β	γ	Anisotropy (λ)
MYC-1	Sericite schist	5.90 ± 2.4	0.98 ± 0.32	0.60 ± 0.16	10:1
MYC-2A	Chlorite-sericite schist	1.56 ± 0.36	3.61 ± 0.9	5.38 ± 0.23	3:1
MYC-2B		7.51 ± 0.74	4.45 ± 0.98	1.96 ± 0.32	4:1
MYC-6	Basalt	3.71 ± 1.48	7.20 ± 2.54	4.47 ± 1.62	2:1
MYC-7	Chlorite schist	13.32 ± 1.68	4.45 ± 0.91	1.94 ± 0.37	7:1
MYC-11	Ore	3.43 ± 0.98	2.42 ± 0.82	2.13 ± 0.52	1.6:1
MYQ-1	Basalt	23.77 ± 1.82	12.50 ± 1.16	7.00 ± 0.76	3:1
MYG-8	Chlorite schist	13.52 ± 0.39	4.24 ± 0.05	2.07 ± 0.02	6:1
MYG-9	Ore	1.69 ± 0.09	0.037 ± 0.003	0.13 ± 0.0	46:1
MYG-11A	Sericite schist	5.08 ± 0.09	0.36 ± 0.0	0.62 ± 0.01	14:1
MYG-11B		1.62 ± 0.05	2.97 ± 0.05	6.61 ± 0.31	4:1
MYG-13	Sericite schist	2.40 ± 0.26	1.25 ± 0.15	0.58 ± 0.02	4:1

ρ_r = Mean bulk electrical resistivity after 24 and 48 hours saturation

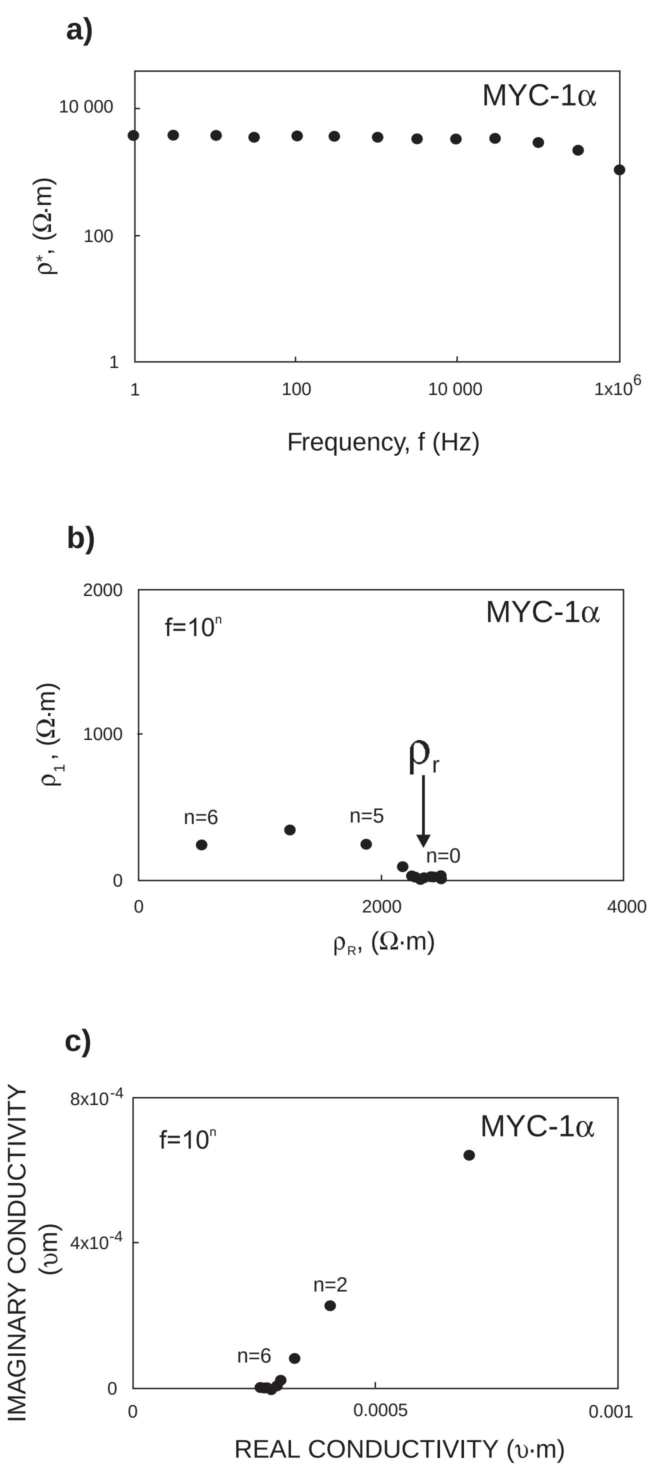

Figure 1. Typical examples of complex resistivity (ρ) plots used to determine bulk resistivity (ρr) for a moderate resistivity sericite schist sample/specimen (MYC-1α):* ***a)*** *ρ* as a function of f,* ***b)*** *ρ_I as a function of ρ_R, and* ***c)*** *imaginary conductivity (σ_I) as a function of real conductivity (σ_R).*

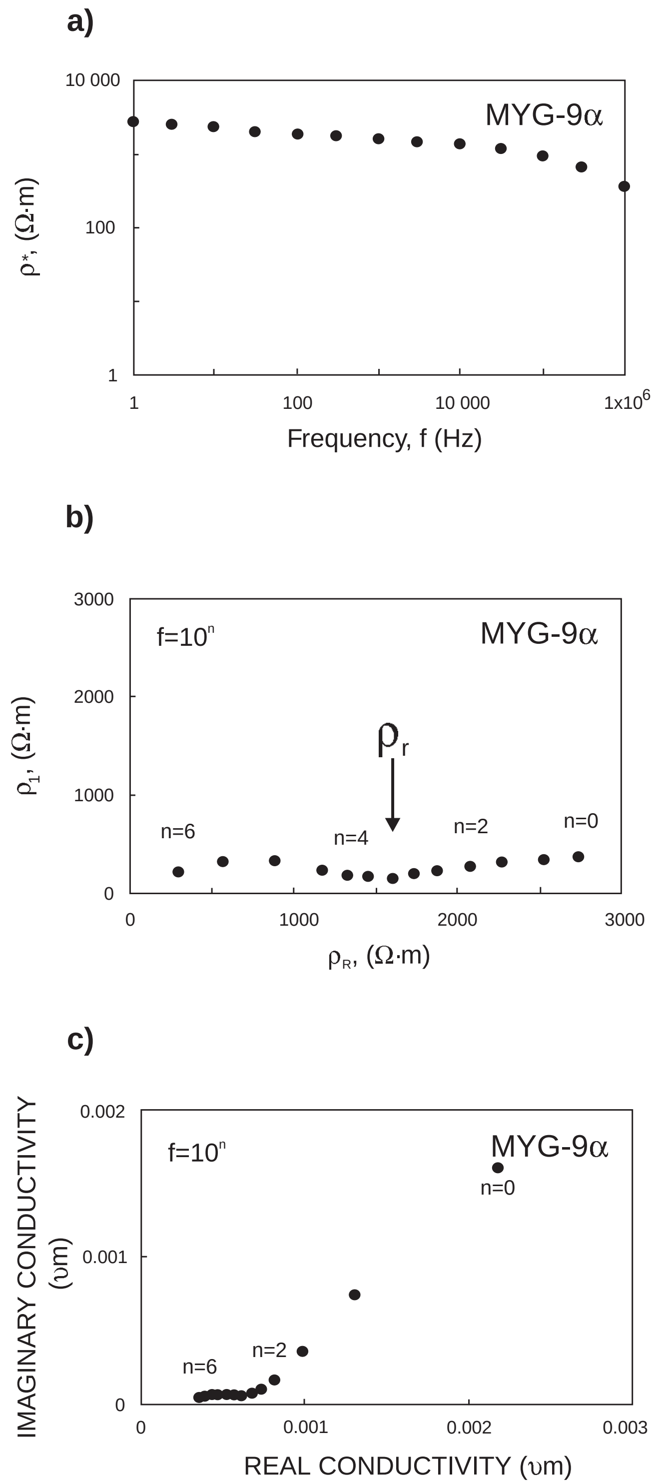

Figure 2. *Typical examples of complex resistivity (ρ*) plots used to determine bulk resistivity (ρ_r) for a high resistivity direction of an ore sample/specimen (MYG-9α):* ***a)*** *complex resistivity (ρ*) as a function of frequency (f),* ***b)*** *imaginary resistivity (ρ_I) as a function of real resistivity (ρ_R), and* ***c)*** *imaginary conductivity (σ_I) as a function of real conductivity (σ_R).*

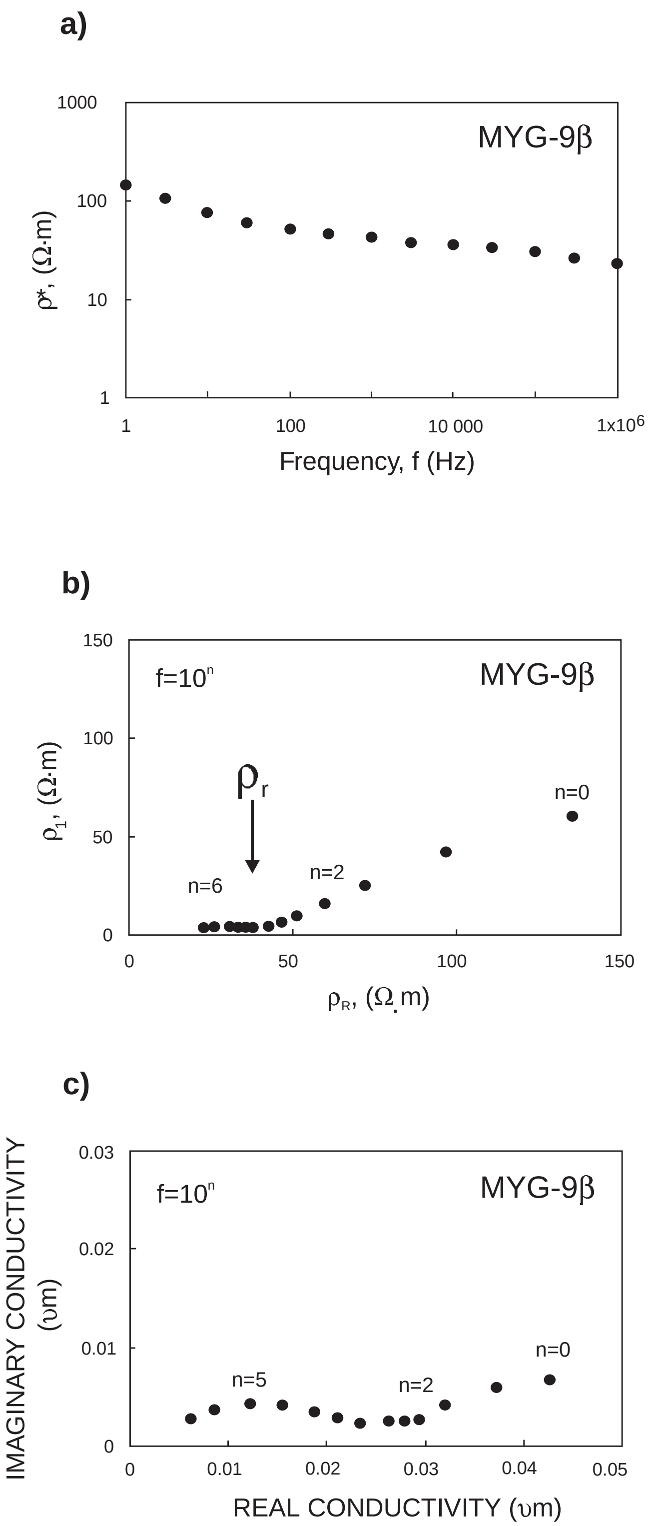

__Figure 3.__ Typical examples of complex resistivity (ρ) plots used to determine bulk resistivity (ρ_r) for a low resistivity direction of and ore sample/specimen (MYG-9β): __a)__ ρ* as a function of f, __b)__ ρ_I as a function of ρ_R, and __c)__ imaginary conductivity (σ_I) as a function of real conductivity (σ_R).*

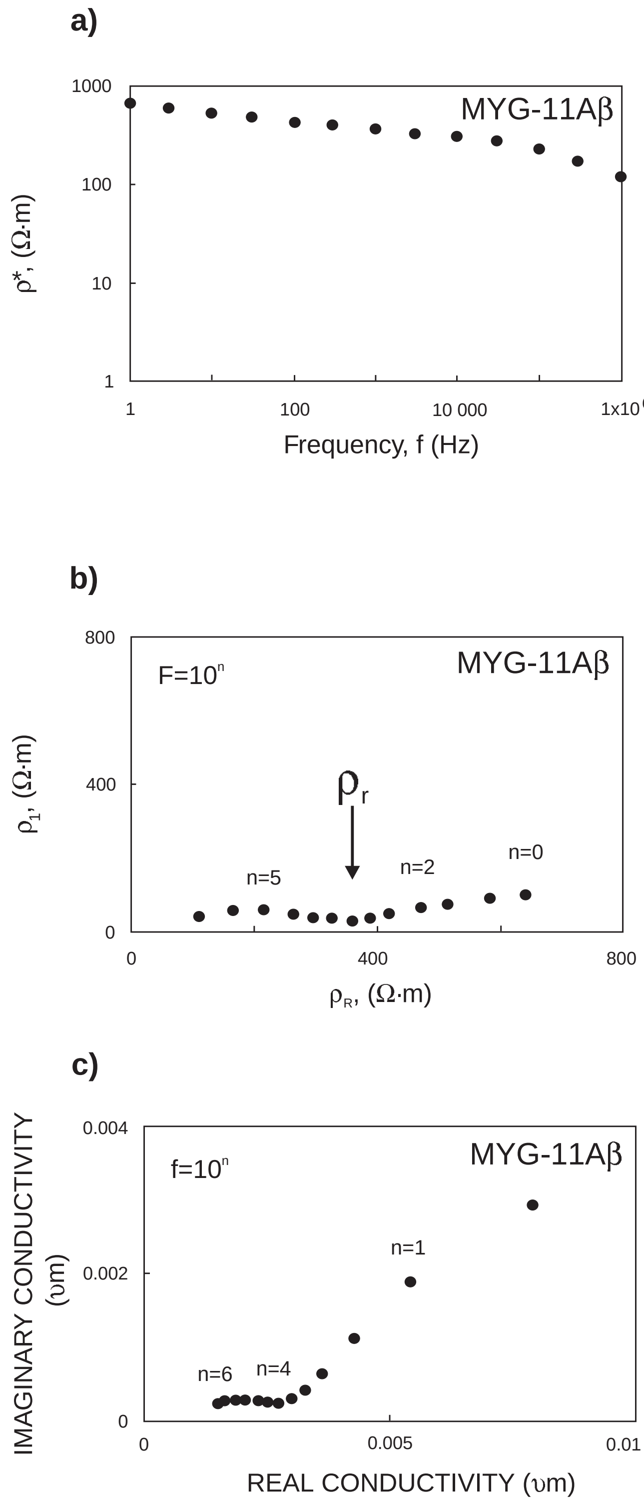

__Figure 4.__ Typical examples of complex resistivity (ρ) plots used to determine bulk resistivity (ρ_r) for a low resistivity sericite-schist sample/specimen (MYG-11Aβ): __a)__ ρ* as a function of f, __b)__ ρ_I as a function of ρ_R, and __c)__ imaginary conductivity (σ_I) as a function of real conductivity (σ_R).*

Table 5a. Results of real (ρ_R) and imaginary (ρ_I) electrical resistivity measurements for samples MYC-1 and MYC-6 over a frequency range of 1–10^6 Hz.

Frequency (Hz)	MYC-1 ρ_R ($10^3\,\Omega\cdot m$)			MYC-1 ρ_I ($10^3\,\Omega\cdot m$)			MYC-6 ρ_R ($10^3\,\Omega\cdot m$)			MYC-6 ρ_I ($10^3\,\Omega\cdot m$)		
	α	β	γ	α	β	γ	α	β	γ	α	β	γ
1	3.749	0.692	0.387	0.039	0.004	0.001	2.715	5.046	2.943	0.081	0.229	0.165
3	3.748	0.691	0.396	0.079	0.010	0.004	2.592	5.045	2.943	0.109	0.247	0.170
10	3.663	0.684	0.400	0.064	0.010	0.004	2.503	4.876	2.976	0.114	0.196	0.187
30	3.621	0.676	0.410	0.063	0.009	0.004	2.391	4.820	2.878	0.088	0.202	0.115
10^2	3.539	0.668	0.414	0.043	0.007	0.003	2.338	4.711	2.845	0.057	0.179	0.118
3×10^2	3.539	0.660	0.429	0.024	0.001	0.0007	2.285	4.659	2.847	0.035	0.116	0.065
10^3	3.499	0.660	0.444	0.003	0.0008	0.0005	2.233	4.660	2.848	0.006	0.038	0.033
3×10^3	3.419	0.645	0.444	0.062	0.006	0.004	2.181	4.500	2.751	0.083	0.215	0.132
10^4	3.380	0.638	0.444	0.098	0.006	0.005	2.079	4.301	2.696	0.153	0.359	0.188
3×10^4	3.262	0.623	0.439	0.281	0.021	0.018	1.928	3.950	2.538	0.296	0.713	0.352
10^5	2.817	0.582	0.396	0.737	0.065	0.050	1.527	2.963	2.025	0.506	1.089	0.473
3×10^5	1.866	0.485	0.322	1.046	0.104	0.064	0.989	1.592	1.305	0.546	1.150	0.558
10^6	0.782	0.335	0.236	0.718	0.097	0.043	0.501	0.630	0.603	0.379	0.575	0.273

ρ_R = Real electrical resistivity after 24 hours saturation
ρ_I = Imaginary electrical resistivity after 24 hours saturation

Table 5b. Results of real (ρ_R) and imaginary (ρ_I) electrical resistivity measurements for samples MYC-11 and MYG-8 over a frequency range of 1–10^6 Hz.

Frequency (Hz)	MYC-11 ρ_R ($10^3\,\Omega\cdot m$)			MYC-11 ρ_I ($10^3\,\Omega\cdot m$)			MYG-8 ρ_R ($10^3\,\Omega\cdot m$)			MYG-8 ρ_I ($10^3\,\Omega\cdot m$)		
	α	β	γ	α	β	γ	α	β	γ	α	β	γ
1	3.450	2.252	2.159	0.338	0.257	0.235	13.58	4.094	2.109	13.58	0.114	0.026
3	3.219	2.126	2.086	0.316	0.242	0.227	13.59	4.191	2.133	13.59	0.088	0.022
10	3.005	1.984	1.969	0.284	0.223	0.214	13.59	4.191	2.109	13.59	0.088	0.029
30	2.807	1.854	1.882	0.236	0.185	0.185	13.43	4.239	2.085	13.43	0.096	0.025
10^2	2.653	1.753	1.758	0.181	0.150	0.154	13.28	4.239	2.061	13.28	0.095	0.018
3×10^2	2.536	1.676	1.681	0.132	0.111	0.120	13.13	4.240	2.061	13.13	0.055	0.010
10^3	2.452	1.603	1.608	0.078	0.068	0.079	13.13	4.289	2.037	13.13	0.023	0.0002
3×10^3	2.311	1.511	1.498	0.156	0.105	0.123	12.51	4.138	1.966	12.51	0.250	0.090
10^4	2.181	1.427	1.382	0.195	0.111	0.135	11.48	3.854	1.853	11.48	0.469	0.170
3×10^4	1.983	1.332	1.274	0.309	0.157	0.186	9.416	3.349	1.664	9.416	0.768	0.282
10^5	1.583	1.125	1.030	0.504	0.265	0.281	5.496	2.351	1.292	5.496	0.933	0.379
3×10^5	0.991	0.792	0.696	0.589	0.358	0.344	2.328	1.384	0.903	2.328	0.820	0.369
10^6	0.440	0.394	0.339	0.377	0.267	0.231	0.817	0.679	0.525	0.817	0.431	0.231

ρ_R = Real electrical resistivity after 24 hours saturation
ρ_I = Imaginary electrical resistivity after 24 hours saturation

Table 5c. Results of real (ρ_R) and imaginary (ρ_I) electrical resistivity measurements for samples MYG-9 and MYG-11A over a frequency range of 1–10^6 Hz.

Frequency (Hz)	MYG-9 ρ_R ($10^3\,\Omega\cdot m$)			MYG-9 ρ_I ($10^3\,\Omega\cdot m$)			MYG-11A ρ_R ($10^3\,\Omega\cdot m$)			MYG-11A ρ_I ($10^3\,\Omega\cdot m$)		
	α	β	γ	α	β	γ	α	β	γ	α	β	γ
1	2.739	0.135	0.248	0.366	0.061	0.054	7.262	0.641	1.196	0.751	0.102	0.209
3	2.525	0.097	0.214	0.346	0.042	0.043	6.782	0.585	1.077	0.653	0.091	0.194
10	2.276	0.072	0.185	0.316	0.025	0.032	6.258	0.516	0.939	0.592	0.075	0.164
30	2.077	0.060	0.165	0.274	0.016	0.024	5.844	0.471	0.838	0.501	0.064	0.136
10^2	1.875	0.051	0.151	0.227	0.097	0.018	5.460	0.420	0.740	0.391	0.050	0.107
3×10^2	1.733	0.047	0.139	0.185	0.065	0.014	5.219	0.388	0.677	0.298	0.040	0.084
10^3	1.601	0.042	0.129	0.145	0.042	0.011	4.988	0.359	0.611	0.200	0.032	0.067
3×10^3	1.457	0.038	0.114	0.163	0.037	0.012	4.697	0.327	0.556	0.404	0.034	0.071
10^4	1.325	0.035	0.106	0.183	0.032	0.012	4.316	0.297	0.494	0.602	0.038	0.075
3×10^4	1.172	0.034	0.098	0.237	0.032	0.014	3.711	0.266	0.431	0.931	0.047	0.091
10^5	0.893	0.031	0.085	0.325	0.040	0.017	2.553	0.218	0.339	1.246	0.058	0.110
3×10^5	0.577	0.026	0.063	0.330	0.041	0.017	1.364	0.164	0.242	1.106	0.057	0.108
10^6	0.298	0.023	0.049	0.219	0.036	0.014	0.564	0.111	0.148	0.584	0.041	0.074

ρ_R = Real electrical resistivity after 24 hours saturation
ρ_I = Imaginary electrical resistivity after 24 hours saturation

DISCUSSIONS AND CONCLUSIONS

The bulk density (δ_B) and effective porosity (ϕ_E) values of these samples are in the ranges of 2.86–3.13 g/mL and 0.40–3.03%, respectively. The larger δ_B values are similar to those of basic rocks and the smaller ones to those of sedimentary rocks (Daly et al., 1966). The smaller ϕ_E values are typical of crystalline rocks (Katsube and Mareschal, 1993; Katsube and Scromeda, 1995) and the larger ones are similar to those of tight sedimentary rocks (Daly at al., 1966). The ϕ_E values of samples taken from the Con mine tend to be smaller (0.40–1.16%) than those taken from the Giant mine (0.42–3.03%).

The bulk electrical resistivity (ρ_r) values are in the range of 37–2.4 x 10^4 $\Omega \cdot m$ for these samples. The lower values are in the range of rocks containing relatively large amounts of sulphide minerals (Keller, 1982), and the higher values are typical of crystalline rocks (Katsube and Hume, 1987, 1989; Katsube and Mareschal, 1993). All samples are moderately to strongly foliated, except for the basalt samples which have very fine carbonate veins (Connell et al., 2000). Textural characteristics such as these, usually result in moderate to strong electrical resistivity anisotropies, as seen in this case (Connell et al., 2000). The electrical resistivity anisotropy values for these samples range from 2:1 to 46:1.

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