Lei Fu

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EDUCATION

Pursuing a *PhD.* degree in Geophysics, Rice University 2011-present

Master of Science in Geophysics, University of Utah 2009-2011
Concentration: Forward modeling and inversion of electromagnetic problems

Bachelor of Science, University of Science and Technology of China 2005-2009
Major: Geophysics

INTERESTS

Full waveform inversion, mathematical and computational methods to study seismic theory and data processing, and geology

SKILLS

Programming languages: Unix, C, Matlab, FORTRAN
Software: ProMAX, SeisWorks 3D, Groundwater Modeling System (GMS)

RESEARCH

- 2011 Study of the induced polarization effect in time domain using Cole-Cole and GEMTIP models (M.S. thesis)
- 2010 Computer Simulation of the Marine Horizontal Loop Transmitter CSEM and MT Surveys over the Oil Deposit
- 2009 3-D marine controlled-source electromagnetic (MCSEM) IP Inversion
- 2009 Undergraduate thesis “Fast Marching Method in Polar coordinates”
- 2008 Theoretical Calculation of the Earth’s Toroidal Free Oscillations, Institute of Geodesy and Geophysics, Chinese Academy of Sciences (IGGCAS).

Induced polarization effect in time domain: theory, modeling and applications

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Michael S. Zhdanov

CEMI, University of Utah

Outline

1. Introduction
2. Induced polarization effect
3. Cole-Cole model and GEMTIP model
4. Inversion of the time-domain GEMTIP model

    4.1 Two-phase model
    4.2 Two-phase model with 2% random noise
    4.3 Three-phase model

5. Experimental analysis of rock samples
6. Conclusion

Introduction

1. Introduction

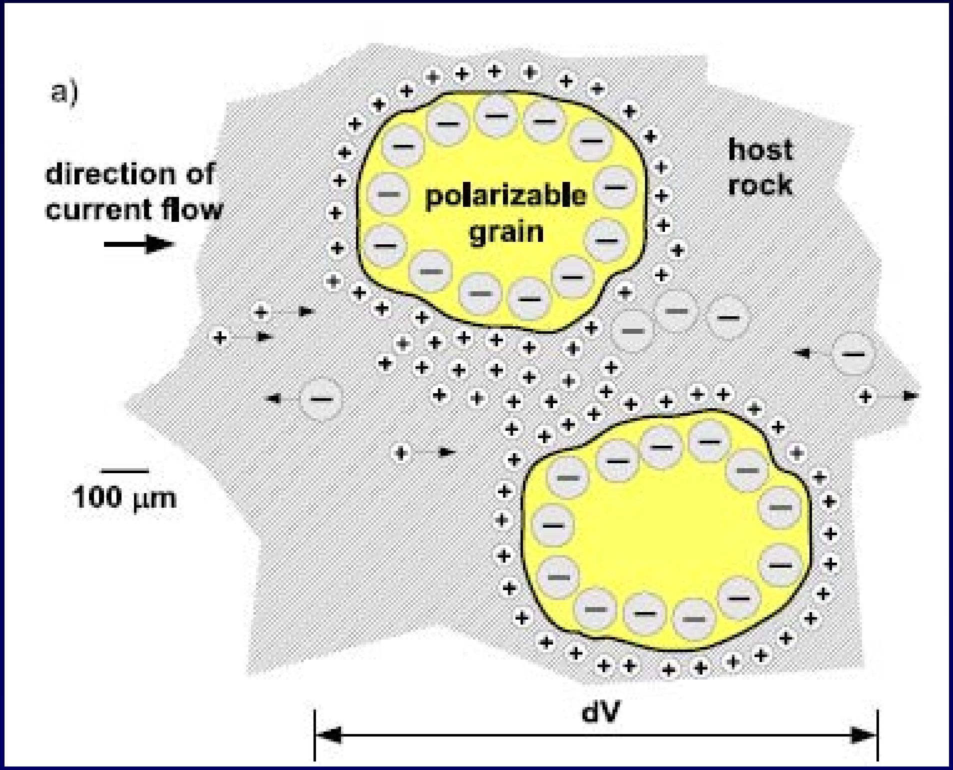
Induced polarization (IP) phenomenon has long been observed in electromagnetic data.

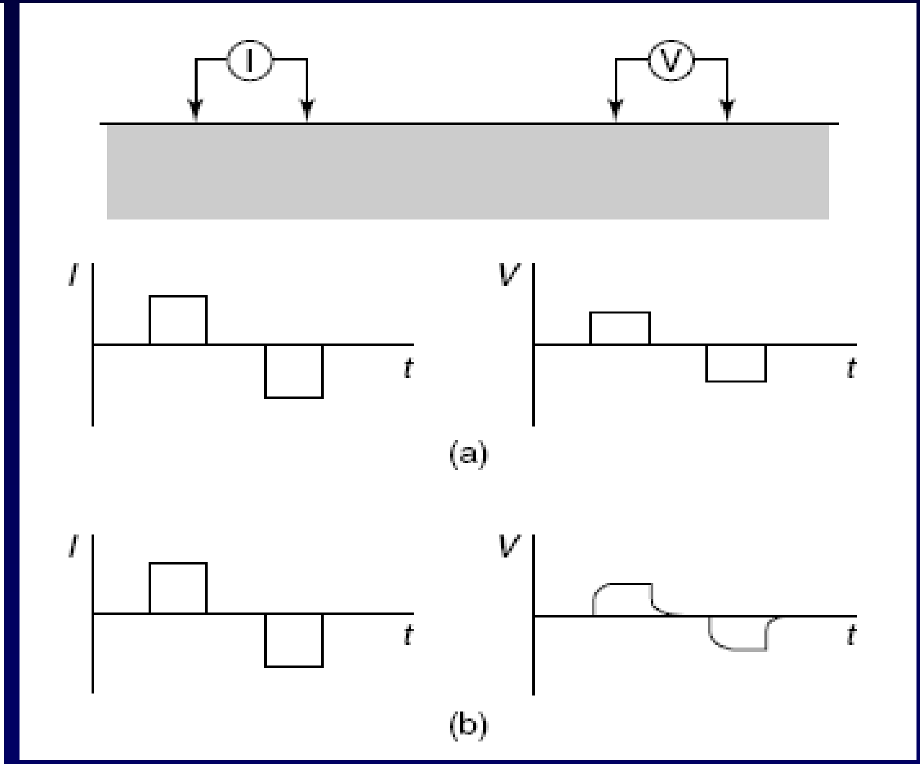
Pelton et al. (1978) empirically introduced the Cole-Cole relaxation model, which has provided a useful framework for the interpretation of EM and IP data over the past 30 years.

Zhdanov (2008) introduced the Generalized Effective Medium Theory for Induced Polarization (GEMTIP).

Induced polarization effect

IP is caused by complex electrochemical reactions that accompany current flow (Frasier,1964):





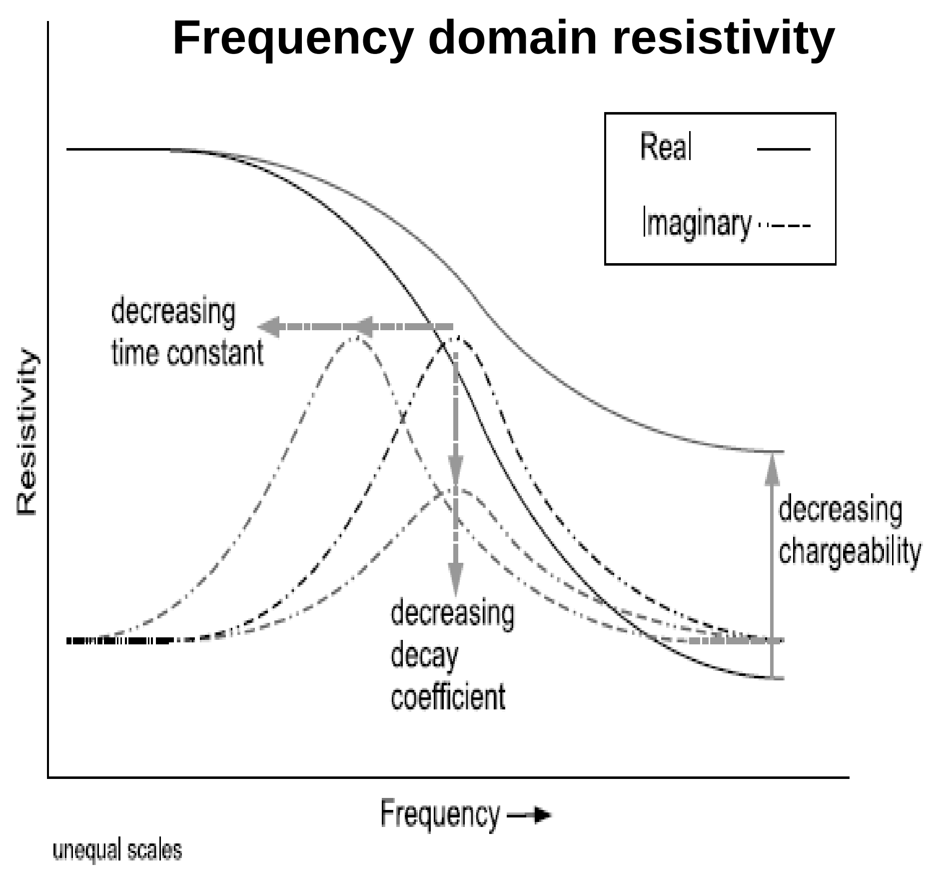
1) Surface polarization of disseminated minerals in a host rock

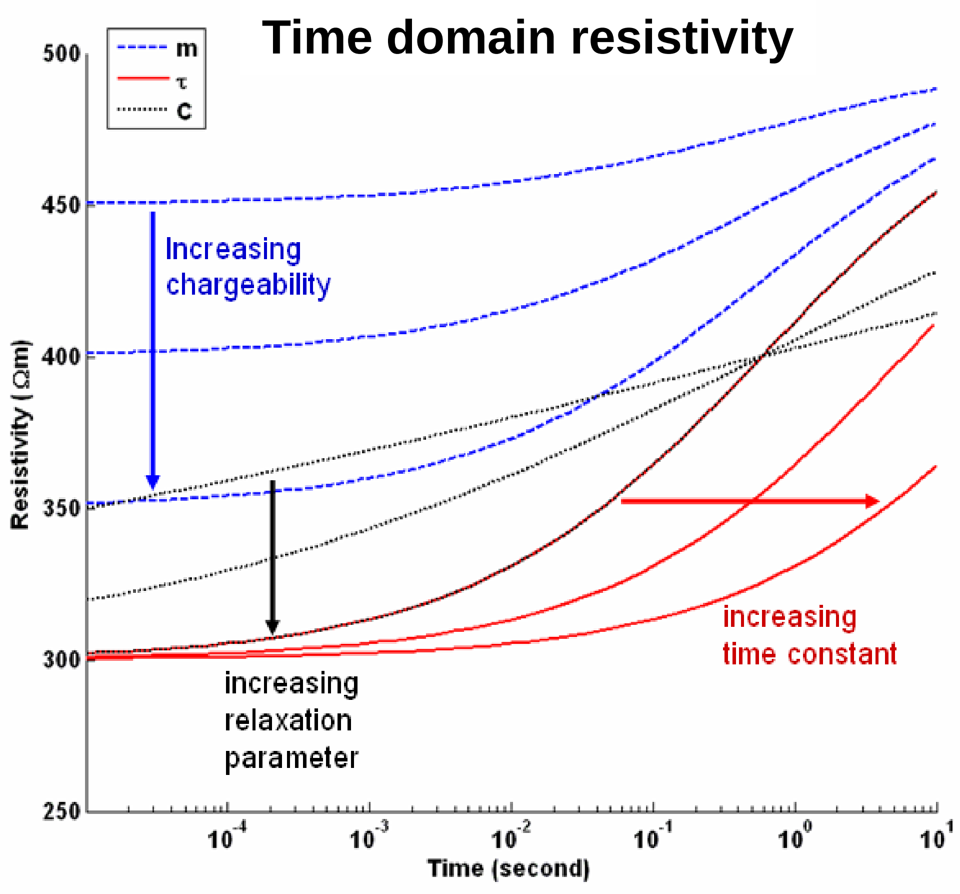
2) Sketch of the potential waveform for a current injected into nonpolarizable and polarizable ground.

Cole-Cole Model

$$\rho(\omega) = \rho_{DC}\left(1 - m\left(1 - \frac{1}{1+(-i\omega\tau)^{C}}\right)\right)$$

Time domain resistivity





(Emond, 2007)

GEMTIP model

The initial goal is to construct the realistic electrical models of the rocks based on the effective medium theory of the multi-phase composite media.

Name: quartz monzonite porphyry (QMP)

Minerals: quartz, feldspar, pyrite, chalcopyrite, (biotite)

5% chalcopyrite

Two-phase time-domain GEMTIP model

Two-phase frequency domain spherical GEMTIP model:

$$\rho_e(\omega) = \rho_0 \left(1 + f_1 m_1 \left(1 - \frac{1}{1 + (i\omega\tau_1)^{C_1}} \right) \right)^{-1}$$

$$m_1 = 3\frac{\rho_0 - \rho_1}{2\rho_1 + \rho_0}, \quad \tau_1 = \left[\frac{a_1}{\alpha_1} (2\rho_1 + \rho_0) \right]^{1/C_1}$$

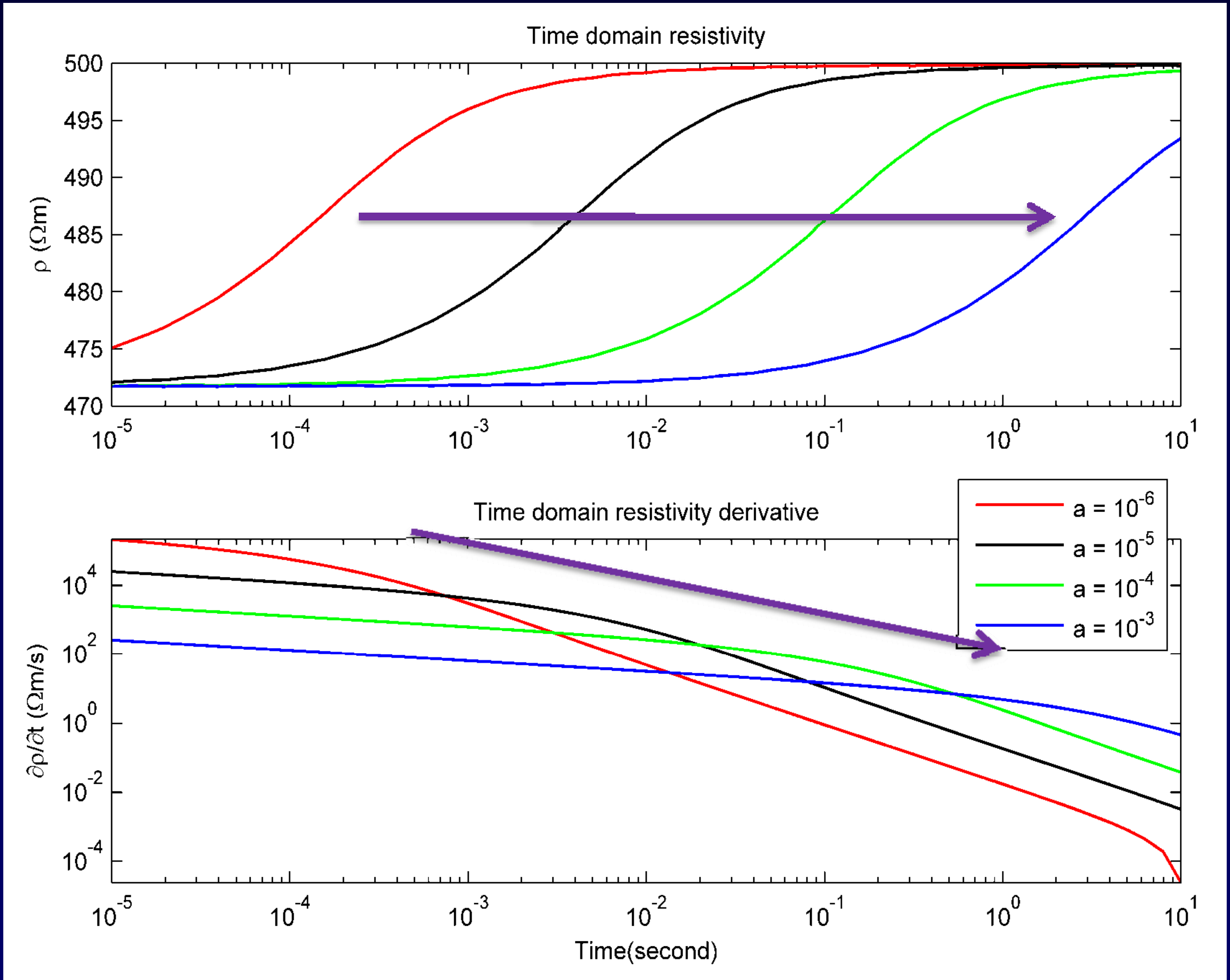
In order to obtain a time domain resistivity curve, one should apply the inverse Fourier transform:

$$\rho_e(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \rho_e(\omega) e^{i\omega t} d\omega$$

Effects of grain radius (a)

Numerical solution for two-phase heterogeneous model:

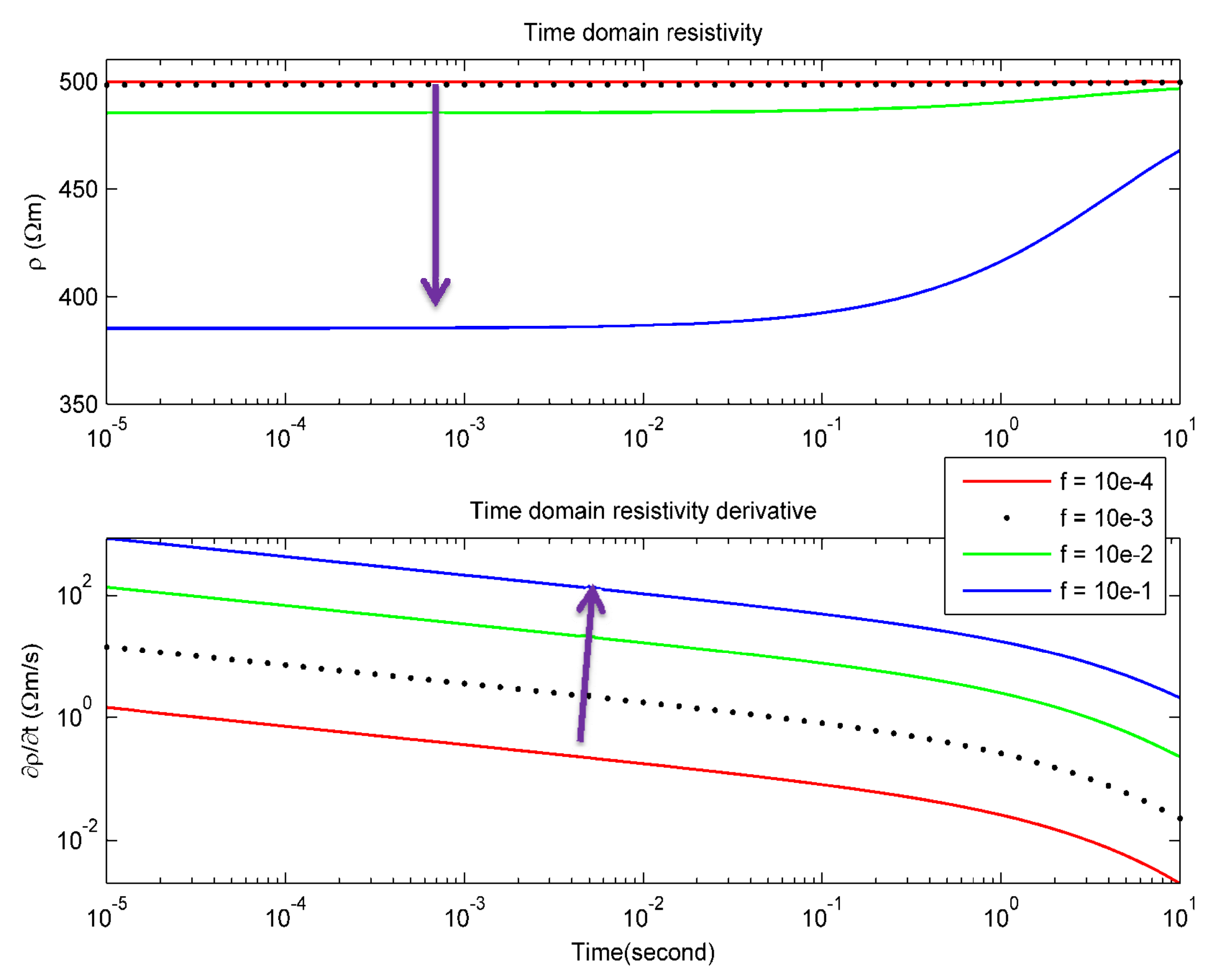
Variable	Unit	Value
ρ_m	Ωm	500
f	-	0.02
C	-	0.7
ρ_1	Ωm	1
α	$\frac{\Omega \cdot m^2}{sec^{cl}}$	0.1



Effects of volume fraction (f)

Numerical solution for two-phase heterogeneous model:

Variable	Unit	Value
ρ_m	Ωm	500
a	mm	0.1
C	-	0.7
ρ_1	Ωm	1
α	$\frac{\Omega \cdot m^2}{\sec^{cl}}$	0.1



Inversion of the time-domain GEMTIP Model

Inversion of the time-domain GEMTIP model

$$\vec{d} = A(\vec{m}) \longrightarrow A^{-1}(\vec{d}) = \vec{m}$$

where **d** is observed data; **m** is model parameter; *A* is a forward modeling operator.

Tikhonov parametric functional

$$P(\vec{m}) = \phi(\vec{m}) + \beta s(\vec{m}) \Rightarrow \min$$

where

$\phi(\vec{m}) = \| A\vec{m} - \vec{d} \|^2$ is a misfit functional

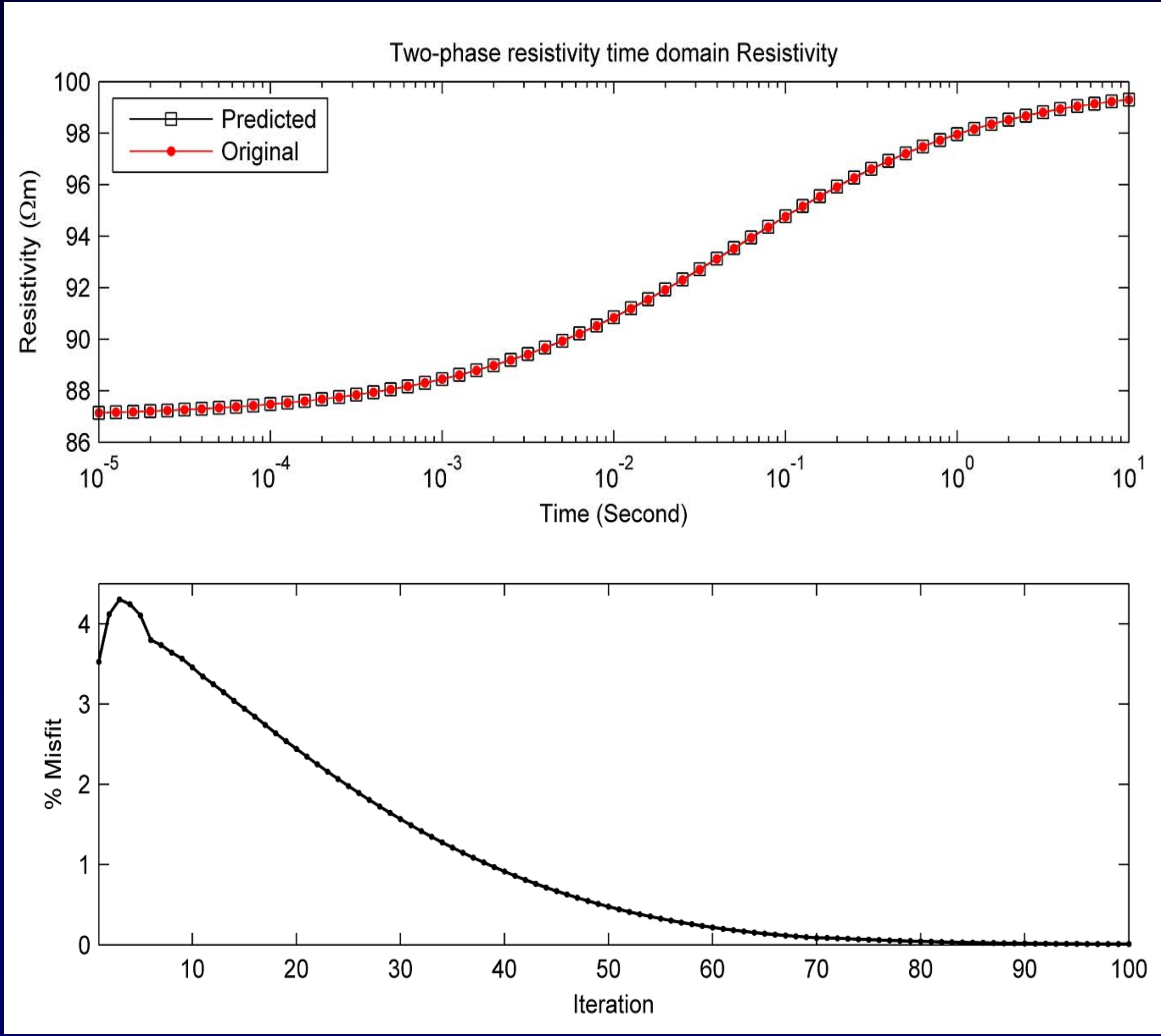
$s(\vec{m})$ is a stabilizing functional

β is a regularization parameter

Regularized conjugate gradient (RCG) method

4.1 Inversion for two-phase GEMTIP model

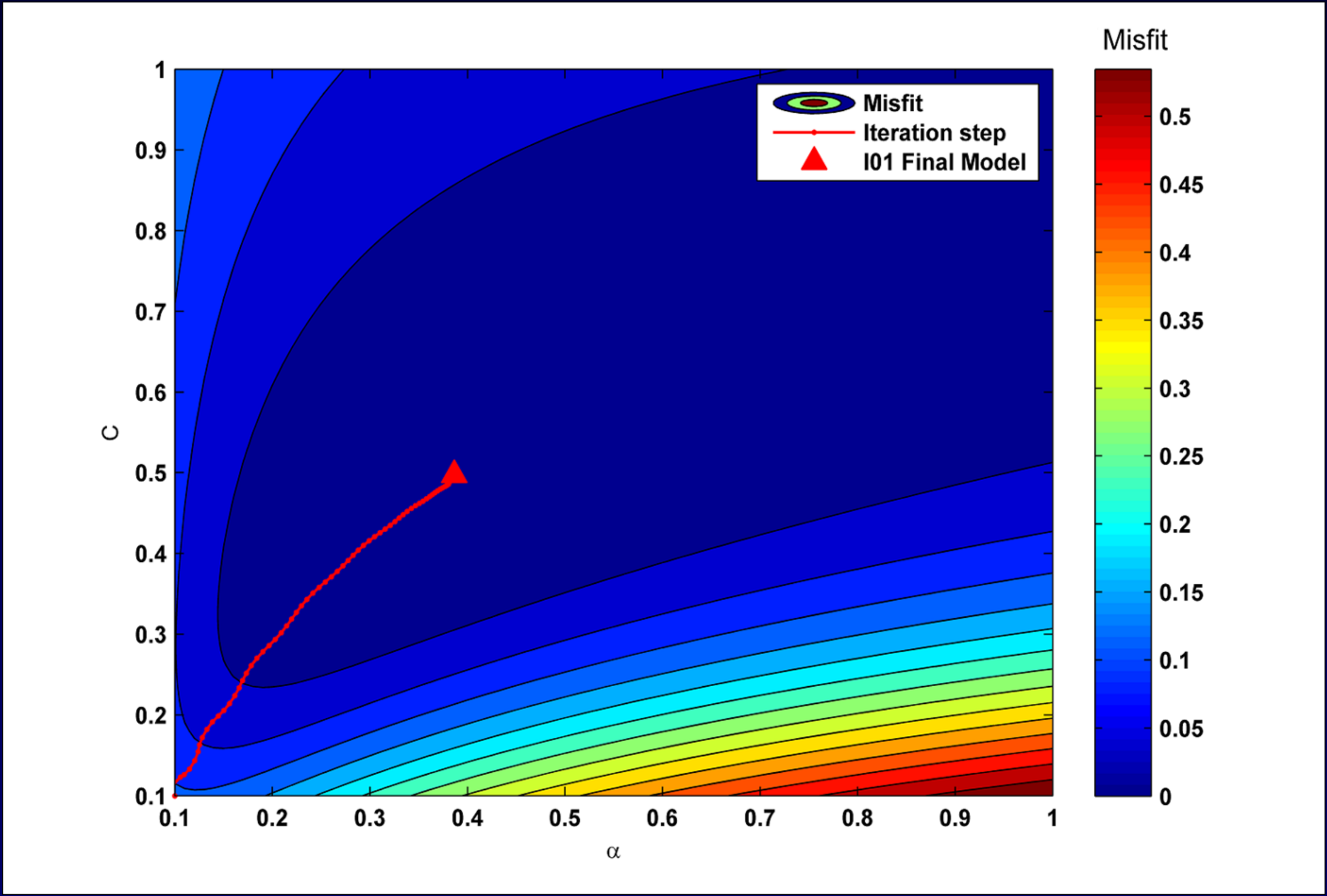
Variable	Units	True model	Initi-al	Reco-vered
ρ_m	Ωm	100	-	-
f	-	0.05	-	-
C	-	0.5	0.1	0.50
ρ_1	Ωm	0.1	-	-
a	mm	2	-	-
α	$\frac{\Omega \cdot m^2}{sec^{cl}}$	0.4	0.1	0.40



Iteration number: 100

Misfit: 0.1%

Misfit functional map

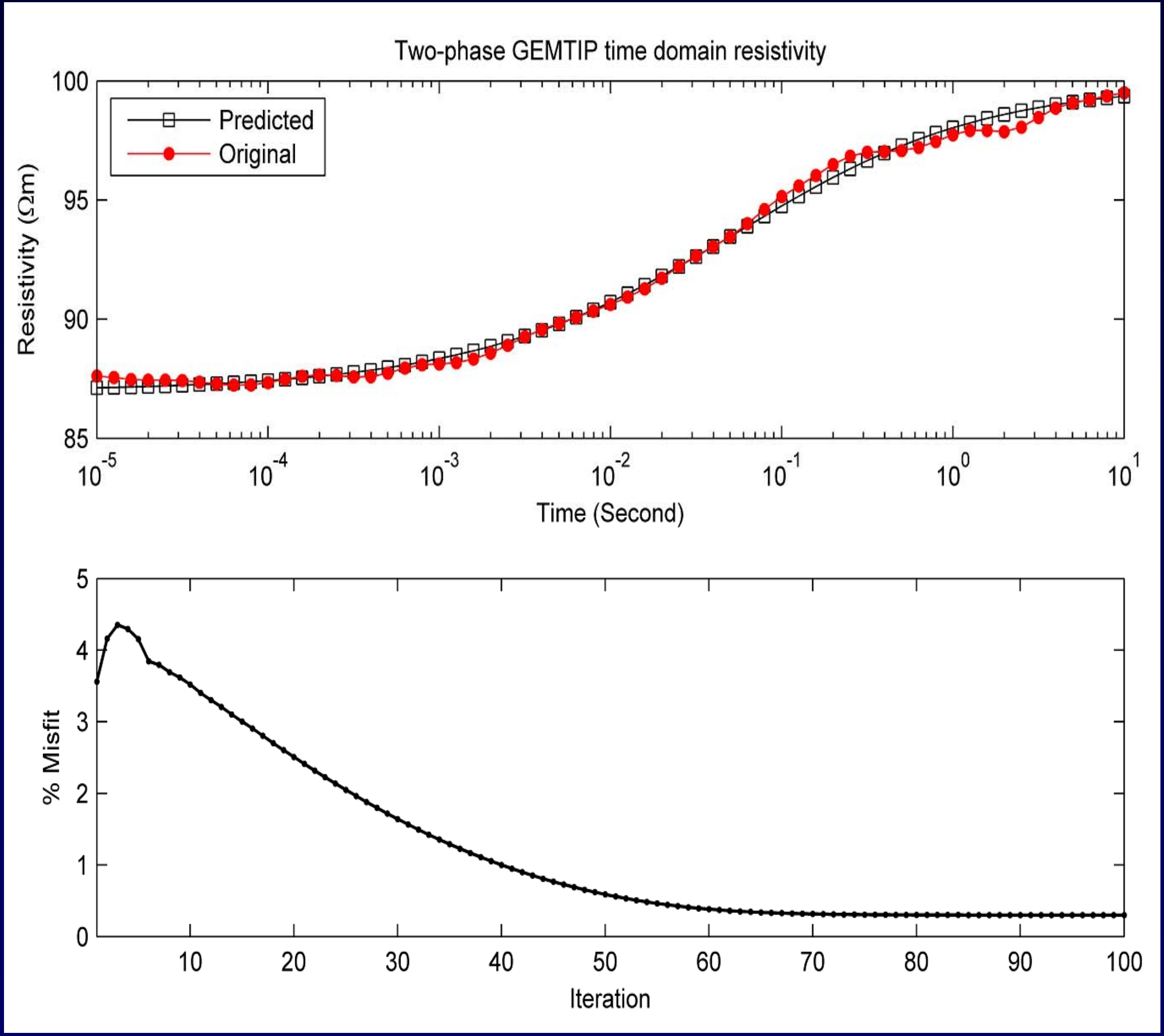


4.2 GEMTIP (2% random noise)

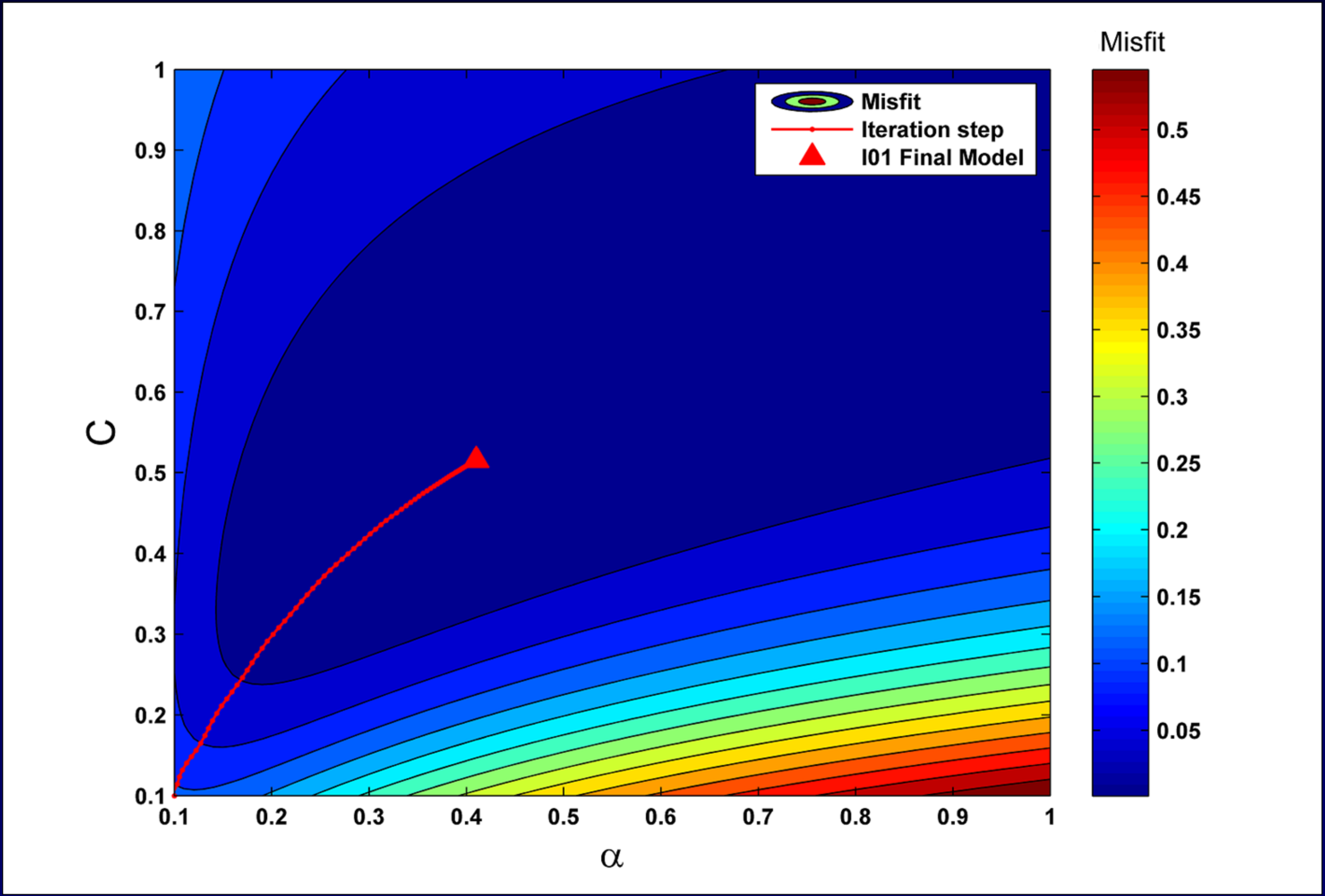
Variable	Units	True model	Initi-al	Reco-vered
ρ_m	Ωm	100	-	-
f	-	0.05	-	-
C	-	0.5	0.1	0.52
ρ_1	Ωm	0.1	-	-
a	mm	2	-	-
α	$\frac{\Omega \cdot m^2}{\sec^{cl}}$	0.4	0.1	0.41

Iteration number: 100

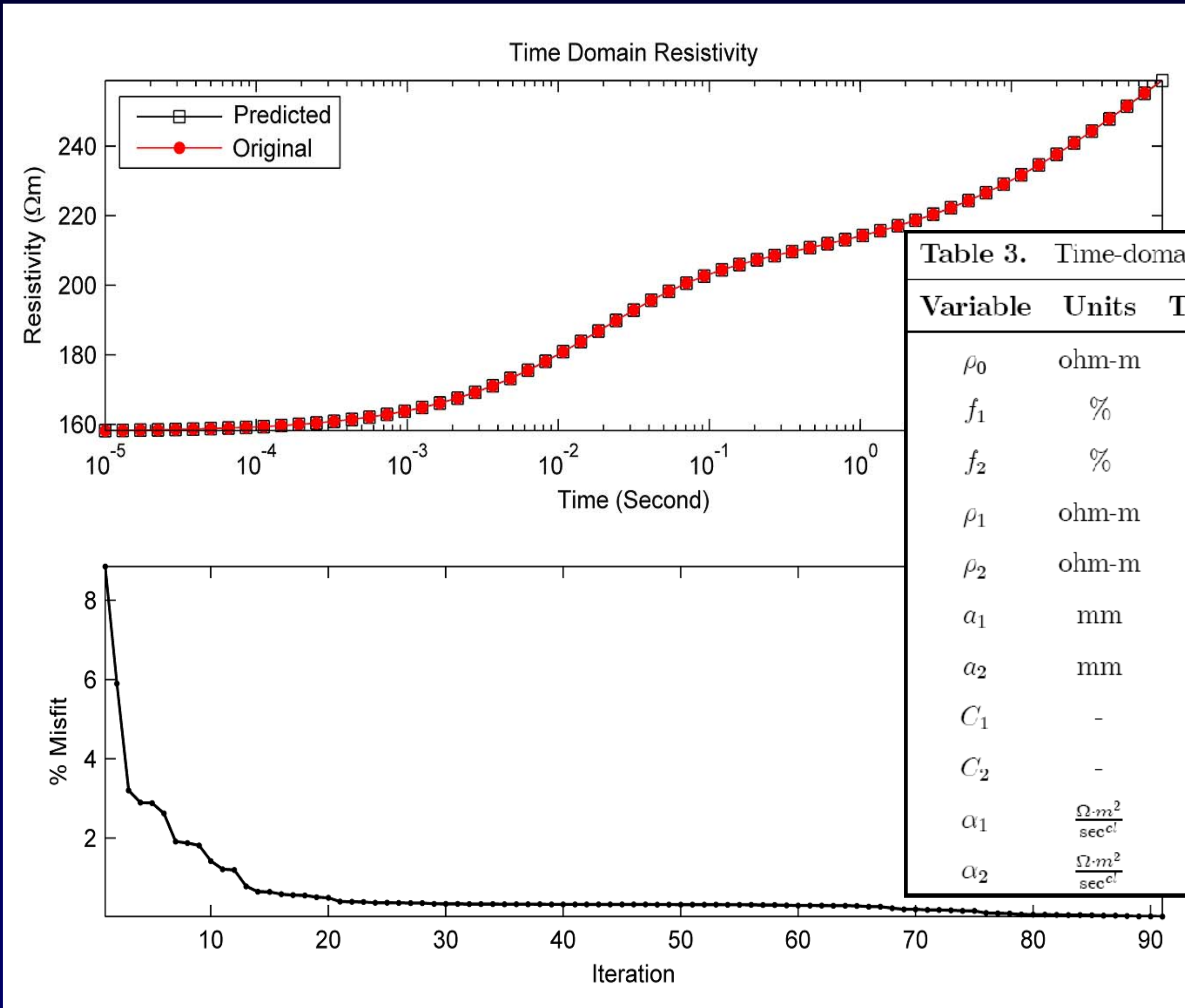
Misfit: 0.3%



Misfit functional map (2% noise)



4.3 Inversion of three-phase GEMTIP model



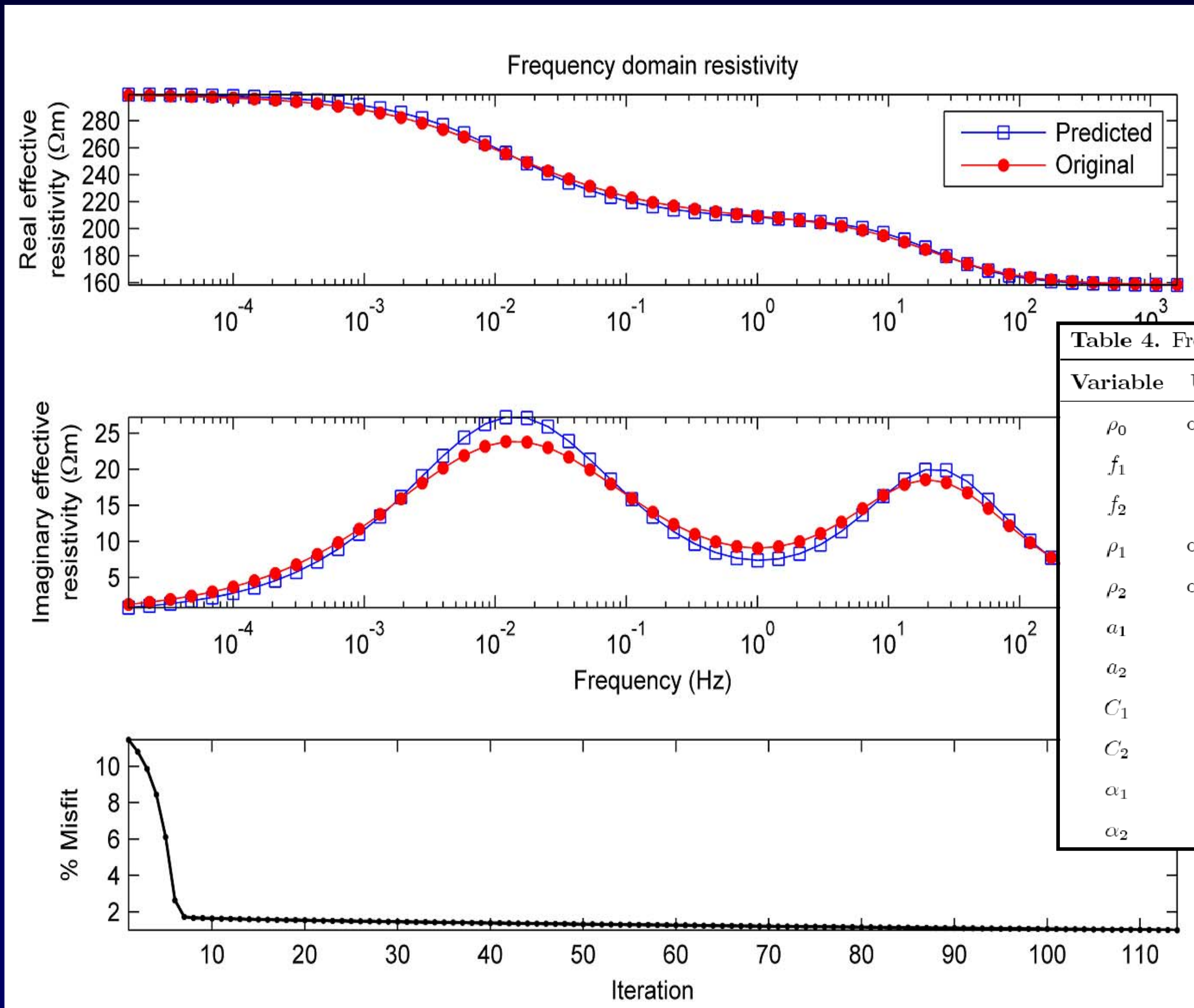
Iteration: 91

Misfit: 0.02%

Table 3. Time-domain GEMTIP model 3 inversion parameters

Variable	Units	True model	Initial	Recovered
ρ_0	ohm-m	300	-	-
f_1	%	15	-	-
f_2	%	15		
ρ_1	ohm-m	0.2	-	-
ρ_2	ohm-m	0.004	-	-
a_1	mm	0.0002	-	-
a_2	mm	0.0008	-	-
C_1	-	0.8	1	0.80
C_2	-	0.6	1	0.60
α_1	$\frac{\Omega\cdot m^2}{sec^{c_l}}$	2	3	1.99
α_2	$\frac{\Omega\cdot m^2}{sec^{c_l}}$	0.04	0.2	0.04

Frequency-domain inversion of three-phase GEMTIP model



Iteration: 114

Misfit: 1%

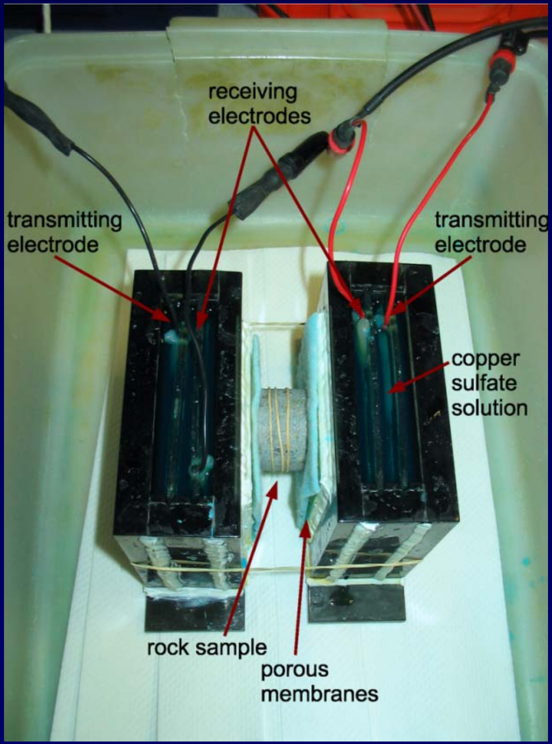
Table 4. Frequency-domain GEMTIP model 3 inversion param

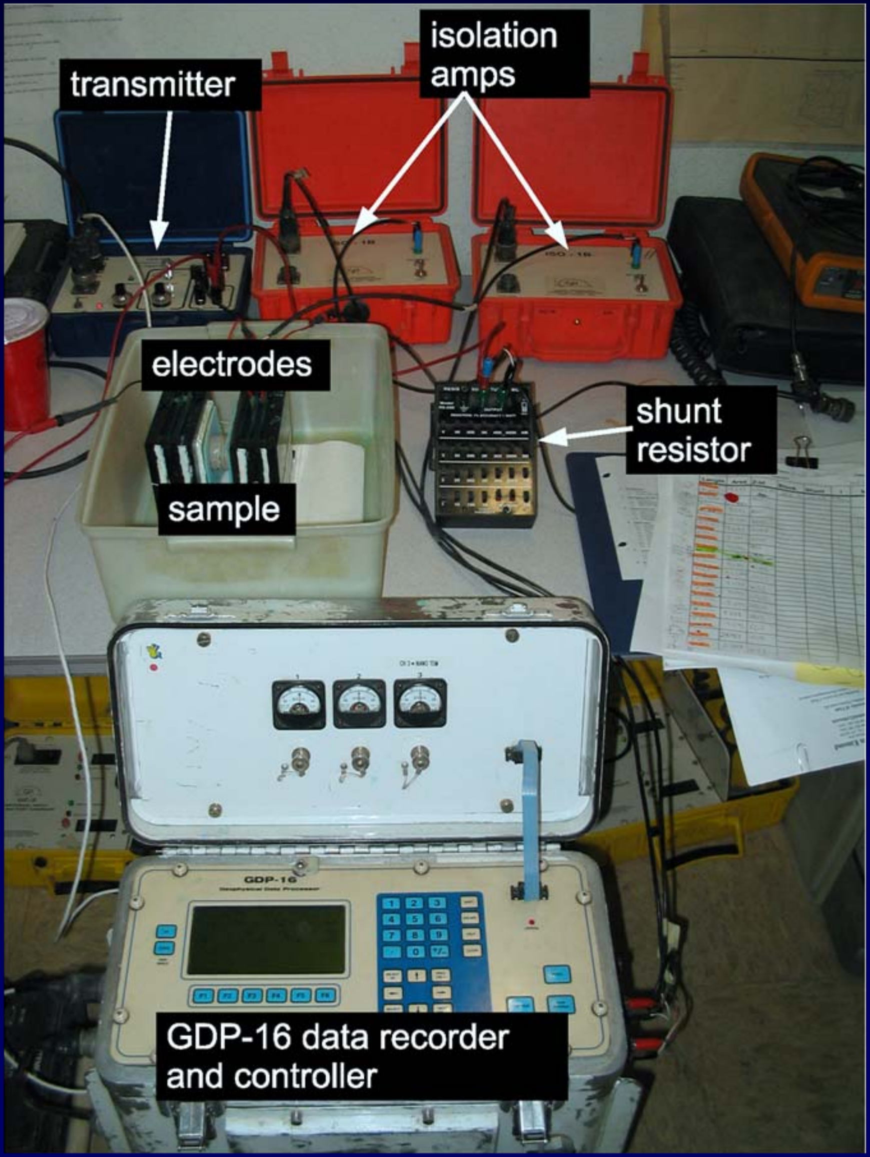
Variable	Units	True model	Initial	Recovered
ρ_0	ohm-m	300	-	-
f_1	%	15	-	-
f_2	%	15	-	-
ρ_1	ohm-m	0.2	-	-
ρ_2	ohm-m	0.004	-	-
a_1	mm	0.0002	-	-
a_2	mm	0.0008	-	-
C_1	-	0.8	1	0.86
C_2	-	0.6	1	0.67
α_1	$\frac{\Omega \cdot m^2}{\sec^{cl}}$	2	3	2.88
α_2	$\frac{\Omega \cdot m^2}{\sec^{cl}}$	0.04	0.2	0.03

Experimental analysis of rock samples

Zonge CR system:

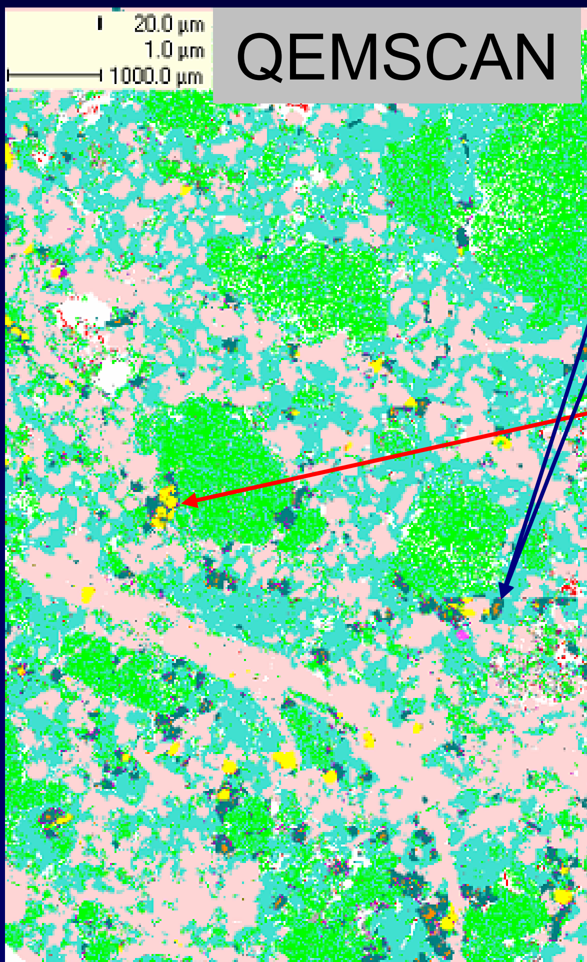
GDP16 receiver; LTD10 transmitter



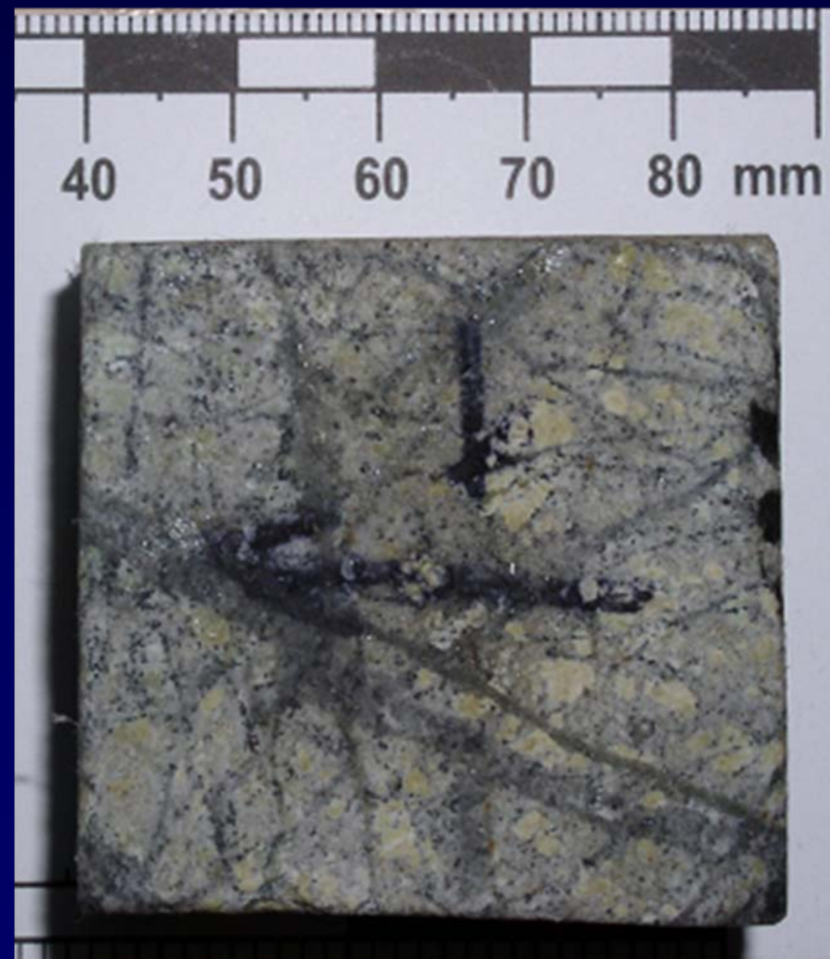


Sample #13

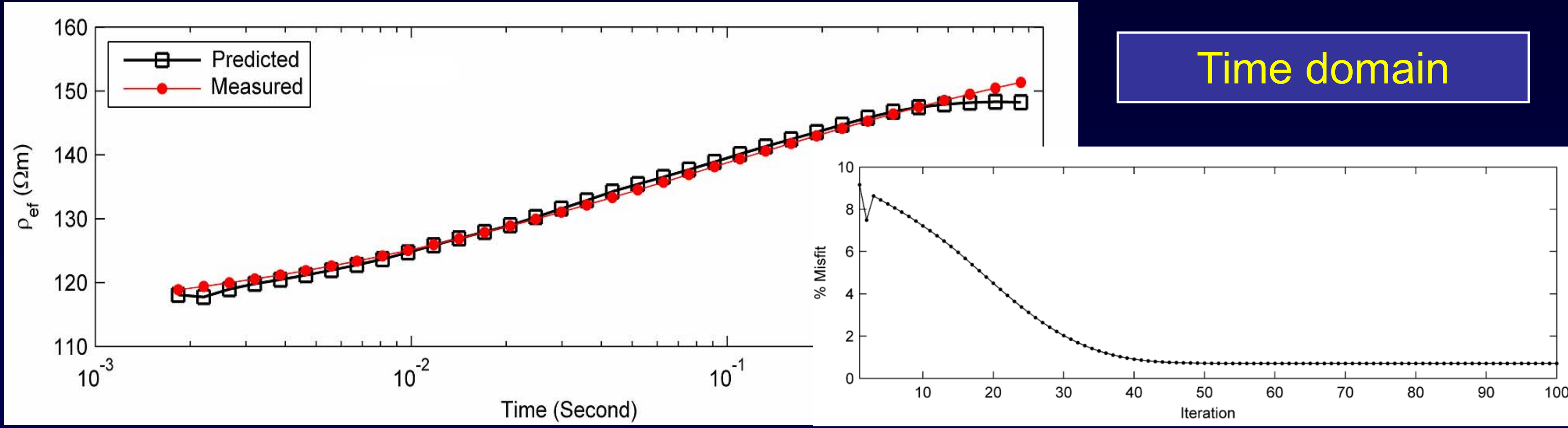
Sar Cheshmeh copper porphyry deposit in Iran
The reflective spots are chalcopyrite and pyrite inclusions.
All sulfides are introduced during vein formation.



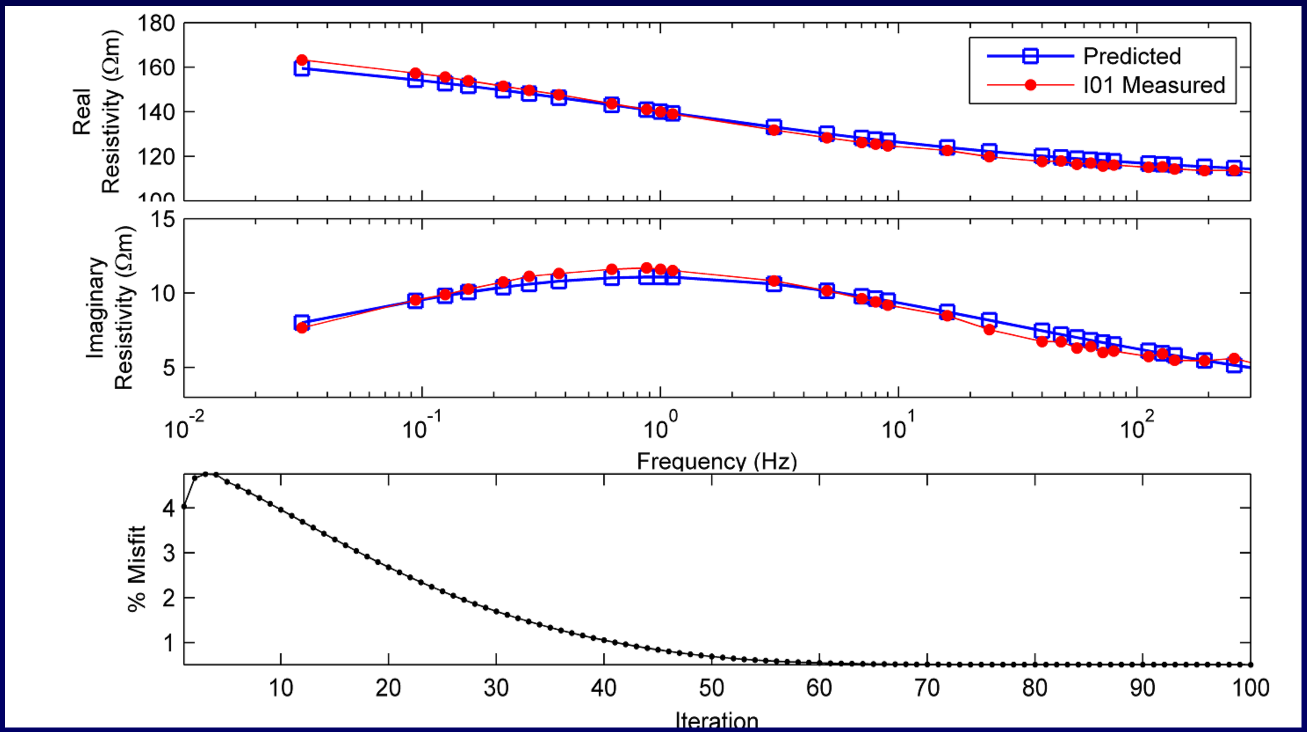
Mineral Name	
Feldspar	41.41
Quartz	30.27
Micas	21.94
Background	9.08
Chalcocite/digenite	3.61
Plagioclase	1.06
Chalcopyrite	0.46
Others	0.41
Pyrite	0.38
Calcite	0.23
Rutile	0.10
Cuprite	0.05
Other_Sulphides	0.03
Pyrrhotite	0.02
Chlorite	0.01
Zircon	0.01
Clay mx	0.01
Biotite	0.00
Other_oxides	0.00
Ce Phosphate	0.00
Goethite	0.00
Apatite	0.00
Olivine	0.00



5.2 Sample #13



Time domain



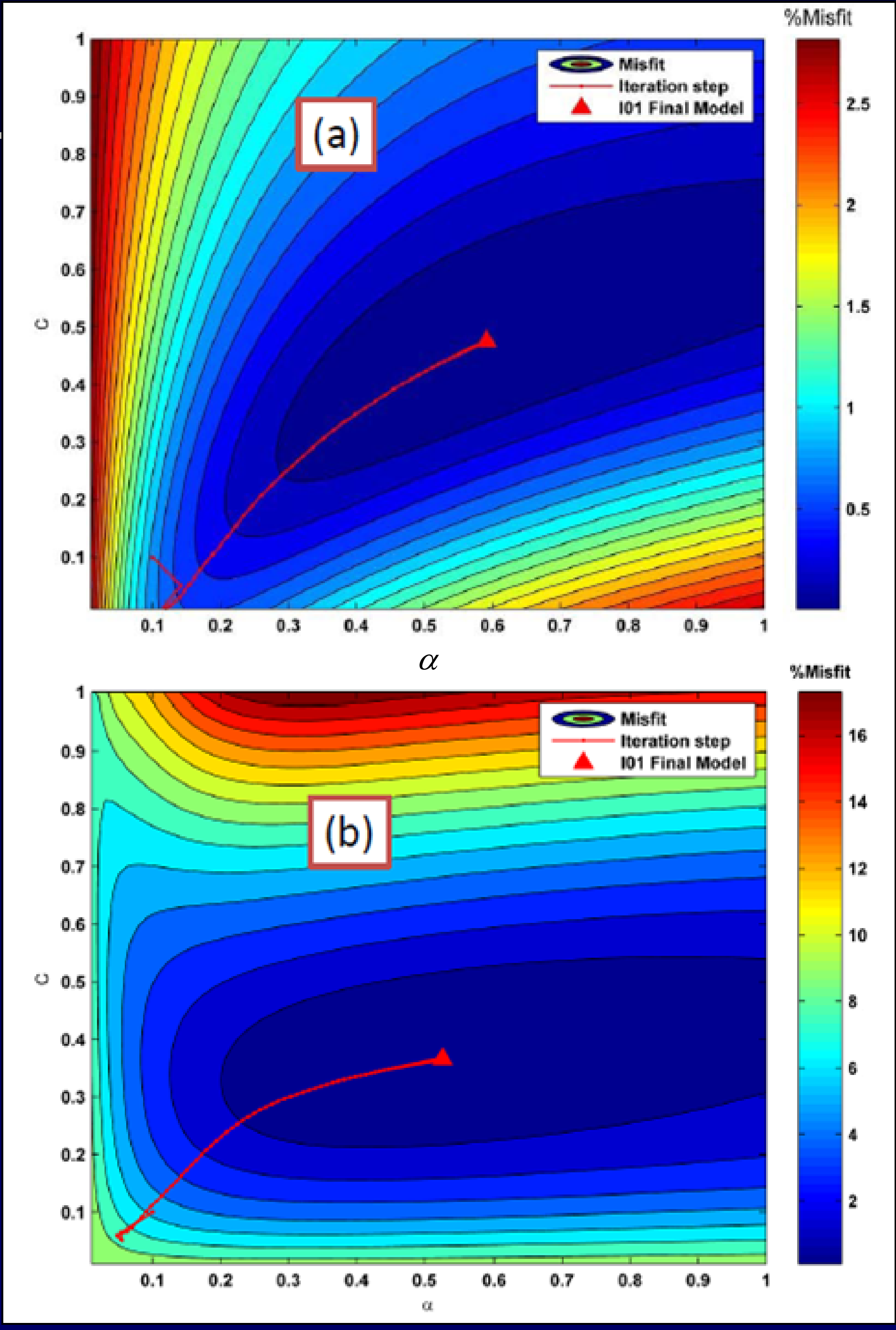
Frequency domain

5.2 Sample #13

variable	Units	Initial model	Time result	Freq result	TD & FD difference
ρ_m	Ωm	163	-		-
f	-	0.05	-		-
C	-	0.1	0.58	0.52	10.3%
ρ_1	Ωm	0.1	-		-
a	mm	0.002	-		-
α		0.1	0.46	0.39	15.2%

a: misfit functional in time domain

b: misfit functional in frequency domain



Conclusion

- I have extended the basic principles of the general effective medium theory of induced polarization (GEMTIP) from the frequency domain to the time domain.

- I have simulated the time-domain resistivity responses for two and three phase heterogeneous media. The IP parameters manifest themselves as peaks in the complex resistivity spectra, or as slopes of the resistivity transients.

- The inversion of synthetic resistivity transients demonstrates that it is possible to discriminate multiple parameters for different mineral inclusions.

Thank you!