Collaborative Research: Hydrogeological-Geophysical Methods for Subsurface Site Characterization

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Collaborative Research

Objective

- Develop methods for “imaging” hydrogeologic parameters.
- Establish the scientific basis for applying shallow seismic and electromagnetic methods to hydrogeolgical problems.

Approach

- Map geophysical parameters using geostatistics.
- Map hydrogeolgic parameters from geophysical parameters using rock physics and geostatiscs.
- Model hydrologic flow using maps of hydrogeologic parameters.

Rock Physics of Shallow Sediments and Bounds for Constraining Porosity

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Stanford Rock Physics Project

Stanford University

Sediment Rock Physics

Motivation

- Reduce cost and risk and increase effectivness of aquifer characterization.
- Bridge gap between petroleum reservoir and hydrogeologic characterization of rock and sediment flow parameters.

Approach

- Use resistivity data to better constrain surface seismic interpretations.
- Integrate electrical and elastic rock physics theory and empirical relationships to better characterize hydrogeologic parameters.

Questions

- How can we best estimate porosity using cost-effective, non-invasive geophysical methods?
- How can we identify changes in lithology and flow properties between hydrogeologic units acoustic and electrical methods?

Electrical Resistivity Background

Electrical currents flow through fluid-filled pore space and conducting minerals (very few common minerals are conductive).

Measurement is controlled by the characteristics of the pore space

- Pore Structure
- Grain Contacts
- Conducting Clays
- Saturation

Electrical Resistivity Bounds

Archies Relationship as Upper Bound

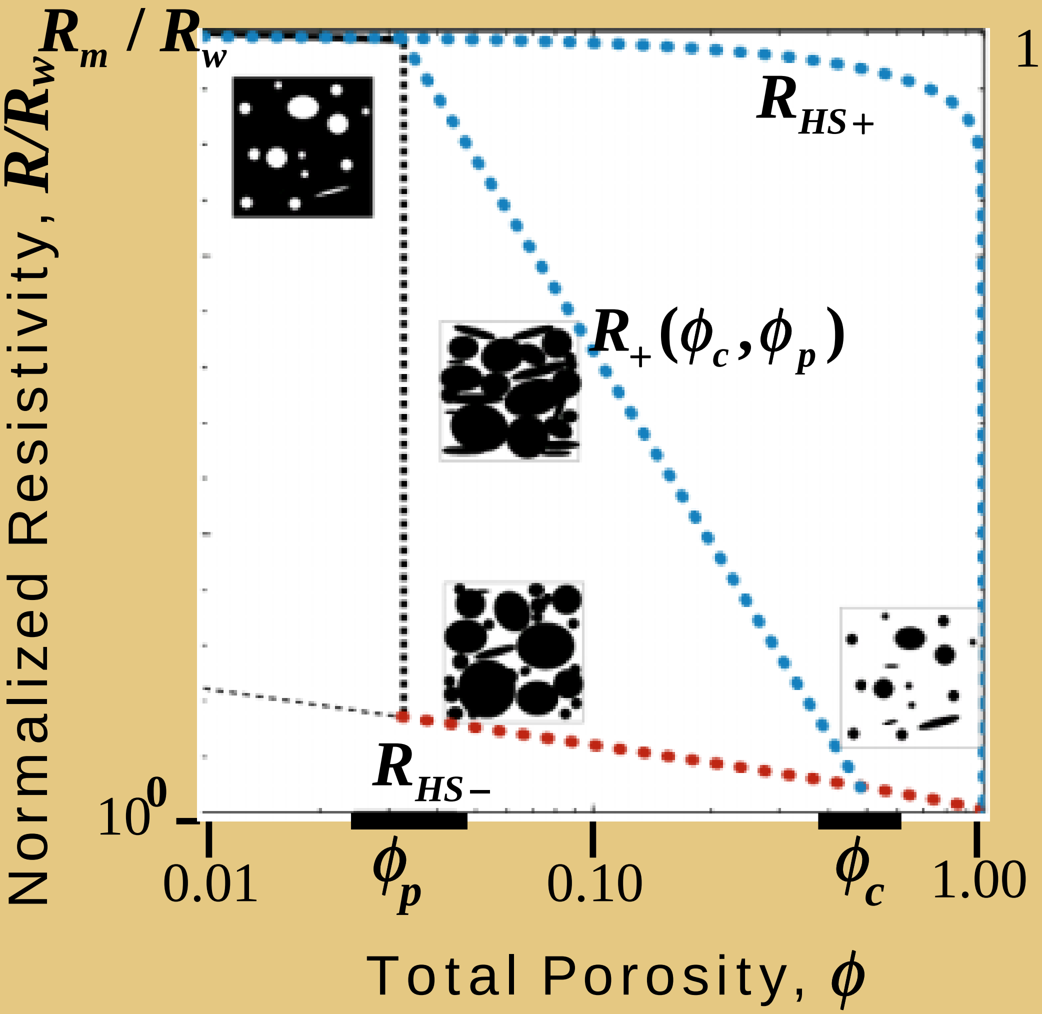
$$R_+ = R_w \frac{a}{\phi^m}$$

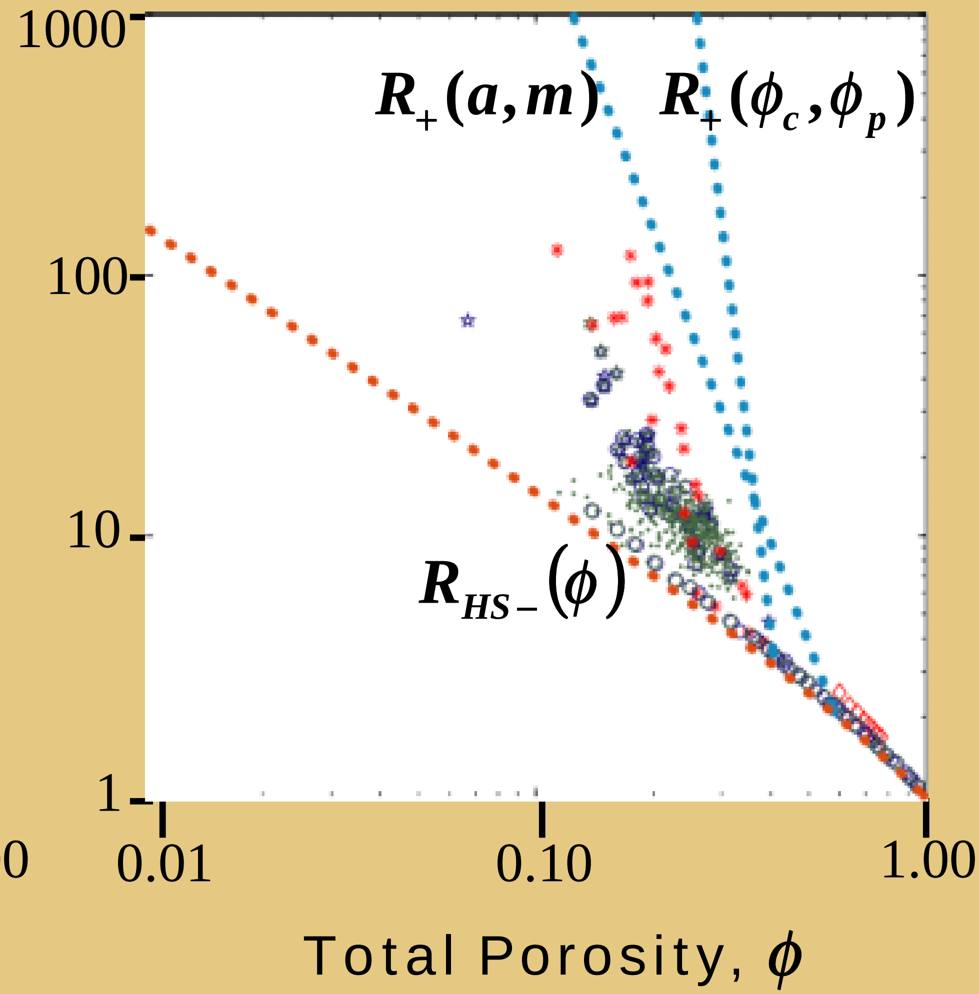
Hashin-Shtrikman Lower Bound

$$R_{HS-} = R_w \left(1 + \frac{3}{2}\frac{1-\phi}{\phi}\right)$$

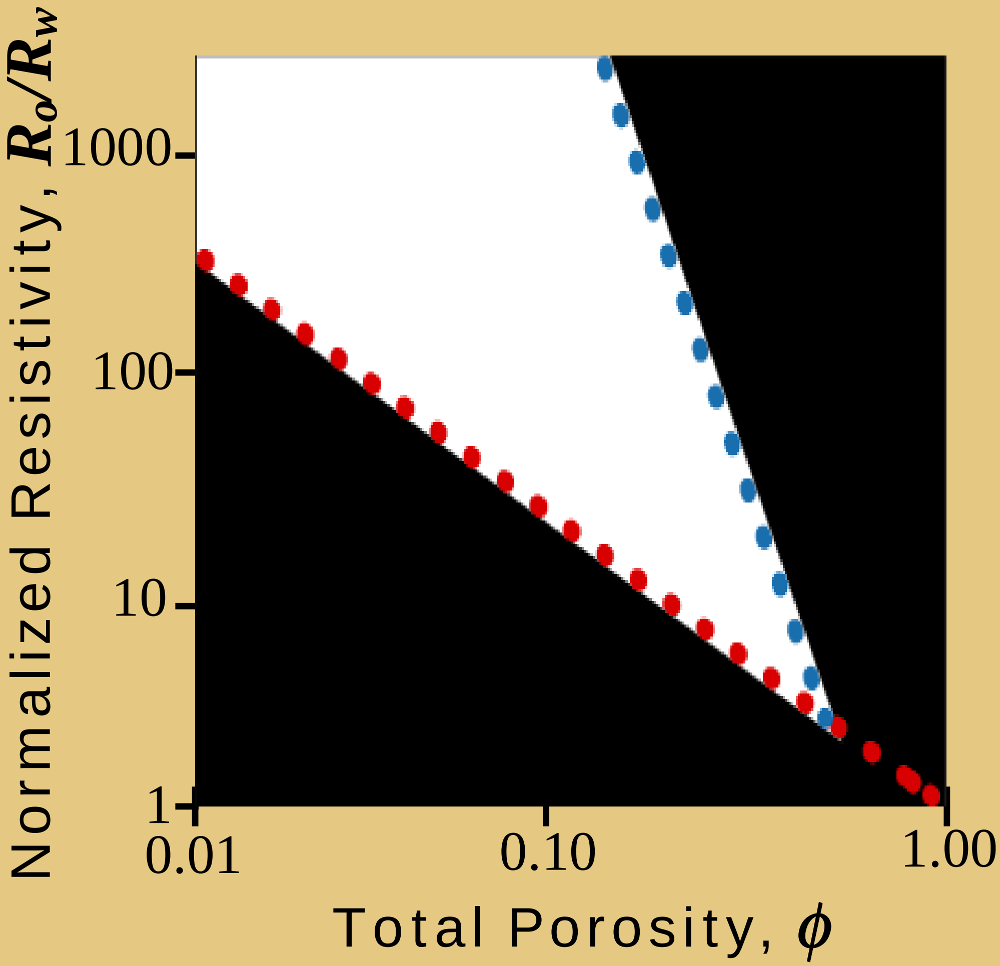
R: true resistivity
R_w: pore-fluid resistivity
ϕ: porosity
a: internal geometry factor
m: cementation exponent

F - ϕ HS Bounds and Empirical Upper Bound





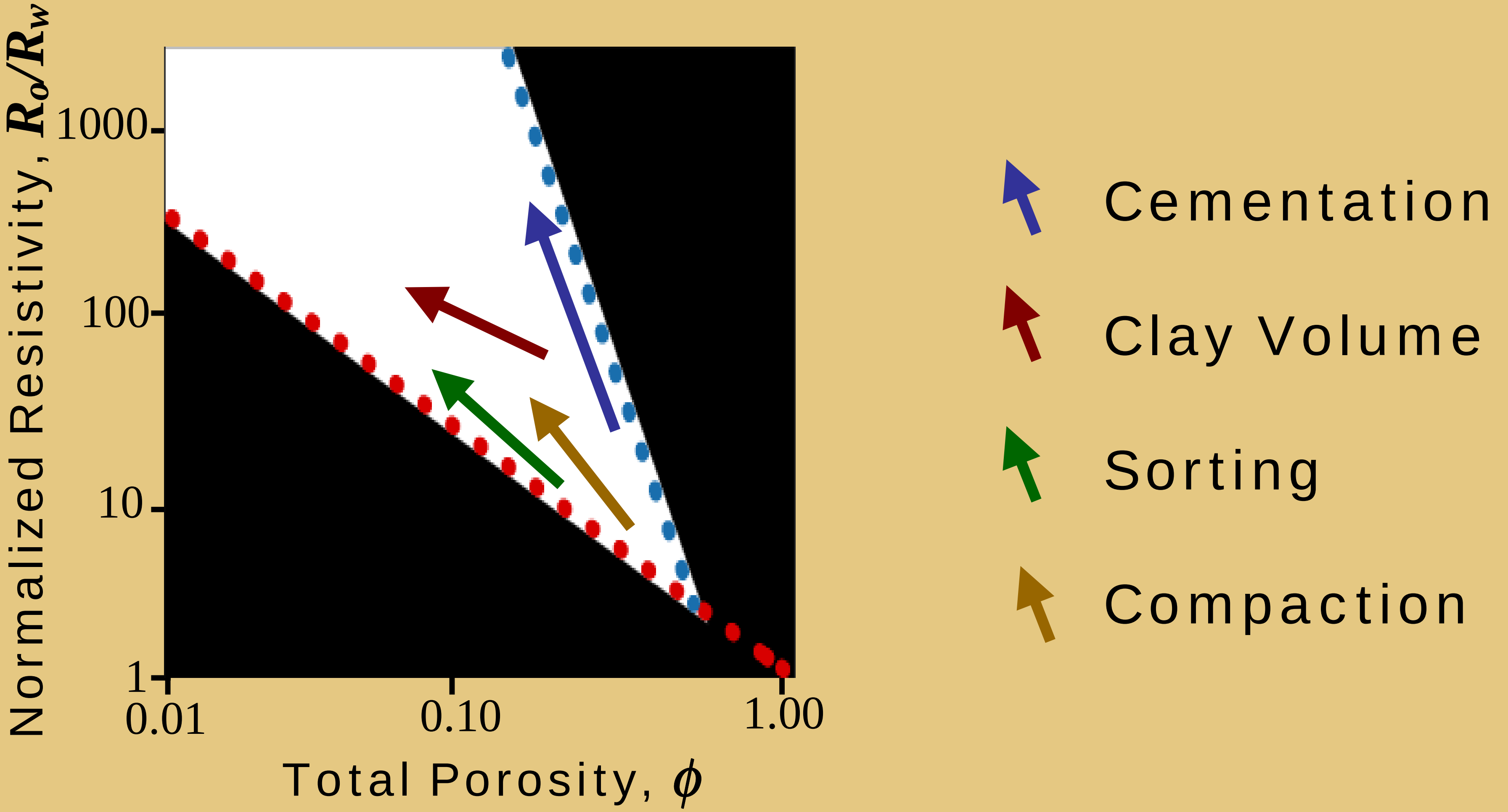
Electrical Resistivity - Porosity Bounds



$$\left.\begin{matrix} R_+(\phi,a,m) \\ R_{HS-}(\phi) \end{matrix}\right\} 0 \le \phi \le 1$$

- Possible region
- Unlikely region
- Empirical Upper Bound, R_+
- HS Lower Bound, R_{HS-}

Electrical Resistivity - Porosity Trends



Acoustic Velocity Background

Acoustic waves travel through pore space AND granular structure.

Stiffness and rigidity are controlled by the bulk characteristics of the material

- Pore Structure
- Grain Contacts
- Mineralogy
- Saturation

Acoustic Velocity Bounds

Compressional Wave Velocity

$$V_{pHS\pm} = \left(\frac{K_{HS\pm} + \frac{4}{3}\mu_{HS\pm}}{\rho} \right)^{\frac{1}{2}}$$

Hashin - Shtrikman Bounds

$$K_{HS\pm} = K_1 + \frac{f_2}{(K_2 - K_1)^{-1} + f_1(K_1 + \frac{4}{3}\mu_1)^{-1}}$$

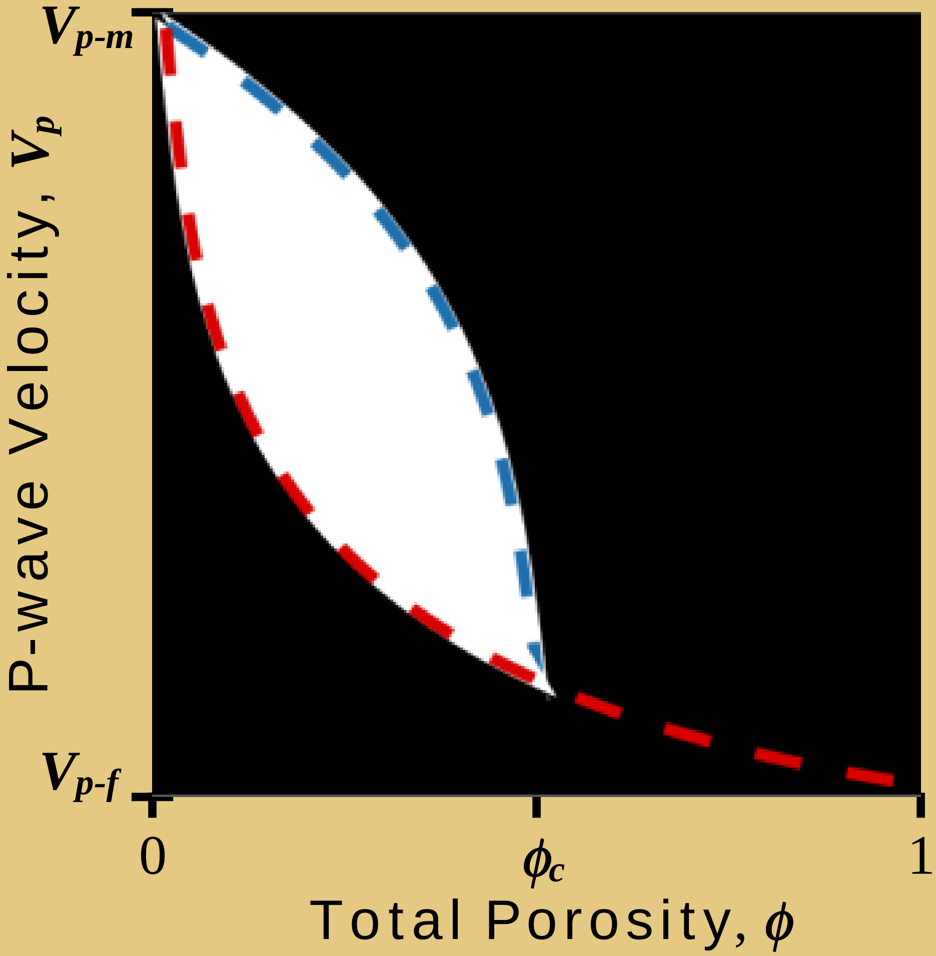
$$\mu_{HS\pm} = \mu_1 + \frac{f_2}{(\mu_2 - \mu_1)^{-1} + \frac{2 f_1 (K_1 + 2\mu_1)}{5\mu_1 (K_1 + \frac{4}{3}\mu_1)}}$$

Bulk Density

$$\rho = f_1\rho_1 + f_2\rho_2$$

V_p: P-wave velocity
K: bulk modulus
μ: shear modulus
ρ: density
f: volume fraction
1,2: constituent index

Acoustic Velocity - Porosity Bounds



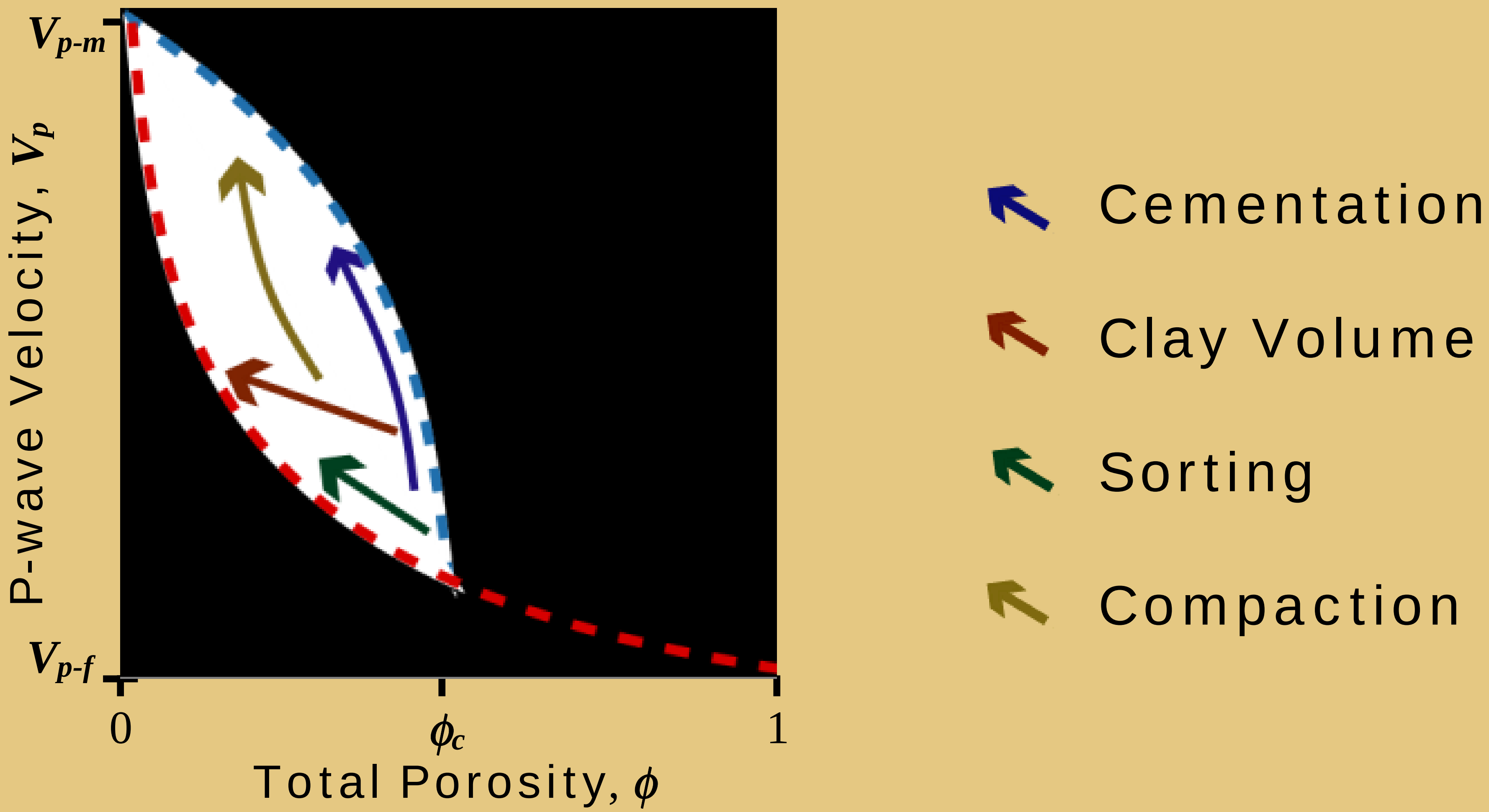
$$V_{pHS\pm}(f_1, f_2, K_1, K_2, \mu_1, \mu_2, \rho)$$

V_{pMHS+}
- $0 \le \phi \le \phi_c$
- constituent 1: mineral
- constituent 2: fluid

V_{pHS-}
- $0 \le \phi \le 1$
- constituent 1: fluid
- constituent 2: mineral

- □ Possible region
- ■ Unlikely region
- MHS Upper Bound, $V_{p\ MHS+}$
- HS Lower Bound, $V_{p\ HS-}$

Acoustic Velocity - Porosity Trends: Diagnose Material



Factors Controlling Resistivity and Velocity

Pore Structure

- amount, texture and content

Grain Contacts

- number, shape and cement

Clays

- amount, type and distribution

Saturation

- amount, type and distribution

Creating R - V_p Bounds

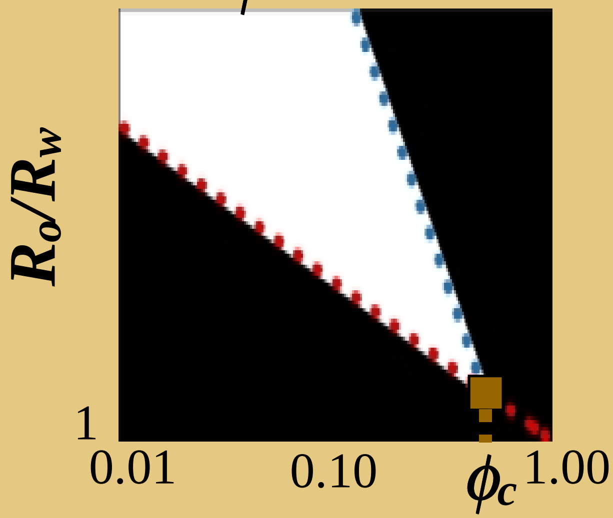
Evaluate upper and lower electrical resistivity bounds at given porosities.

Evaluate upper and lower elastic moduli bounds at given porosities.

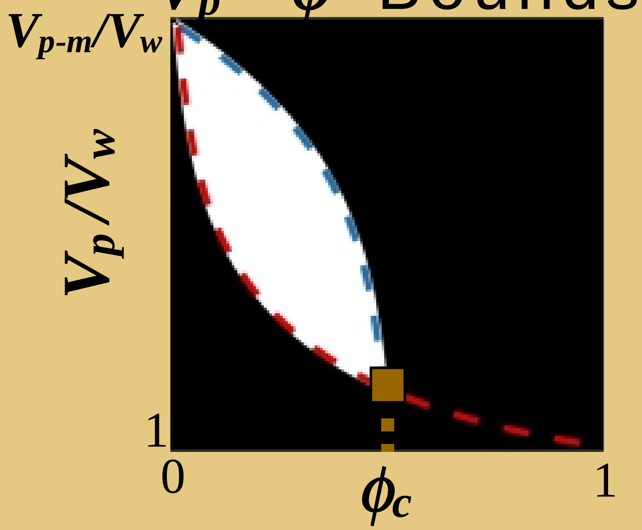
Combine the resistivity and elastic moduli bounds at the same porosities.

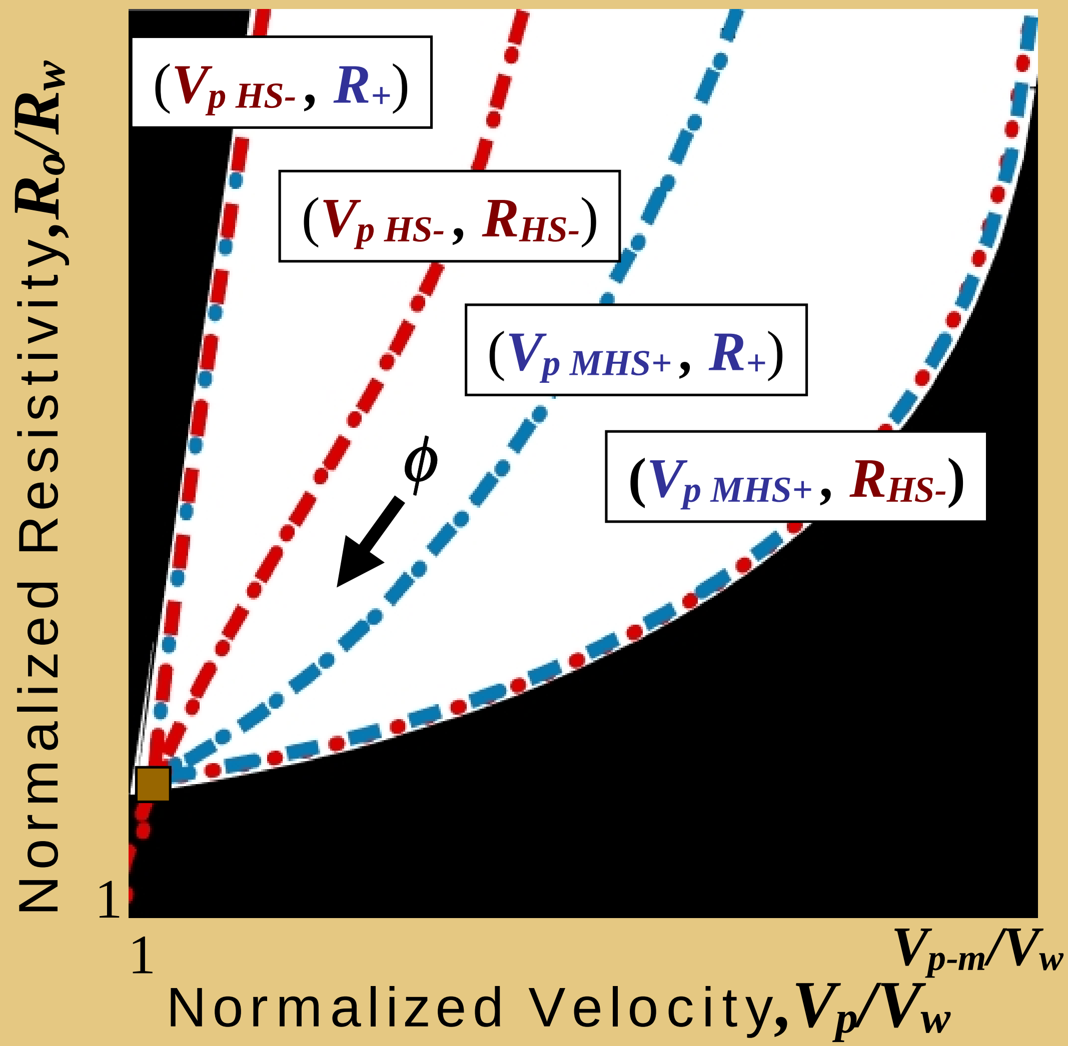
Exploring the R - V_p Relationship

R - ϕ Bounds



V_p - ϕ Bounds





■ Critical Porosity, ϕ_c

Application 1: Constraining Porosity

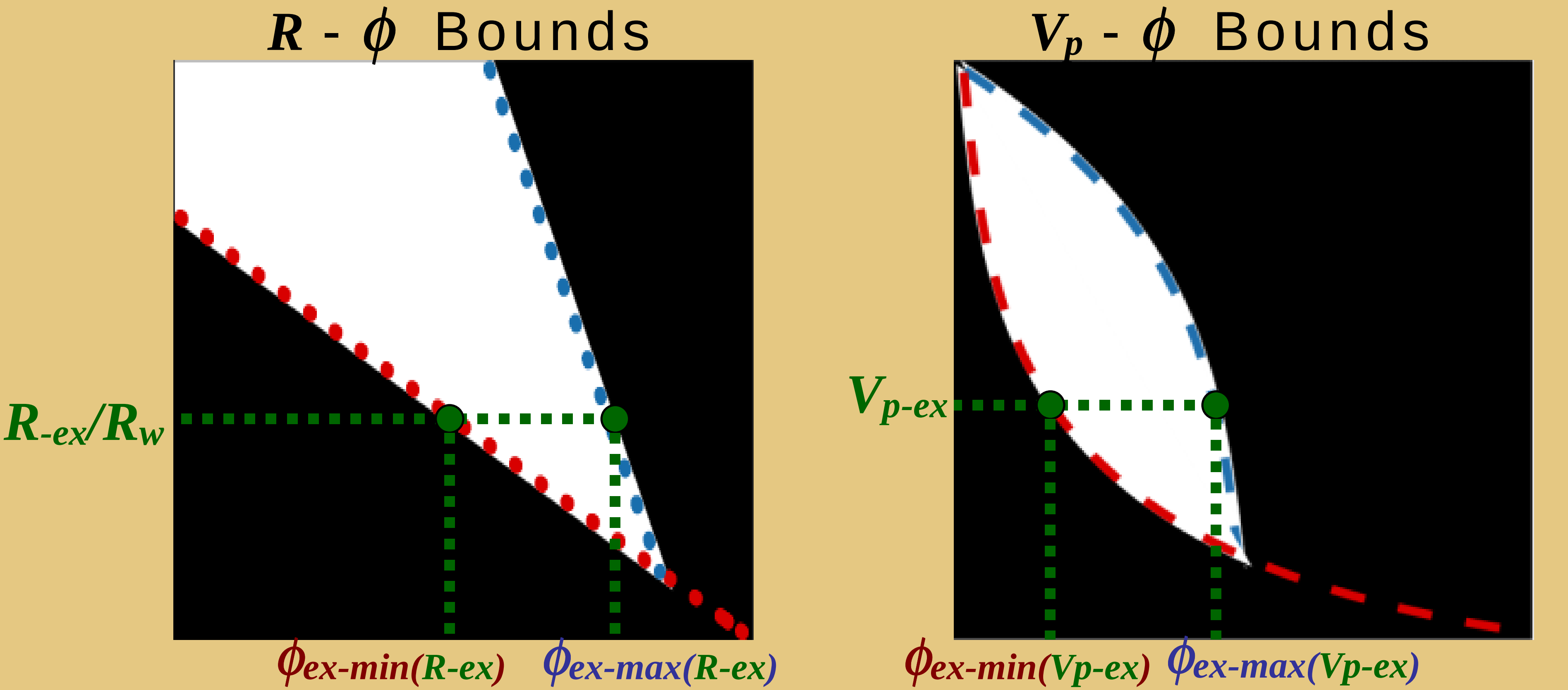
Data:

- Co-located resistivity - velocity (R, V_p) measurement
- Pore-fluid resistivity (R_w)

Parameters for Velocity Bounds:

- Bulk moduli (K_f, K_m)
- Shear moduli (μ_f, μ_m)
- Densities (ρ_f, ρ_m)
- (Optional) Critical porosity (ϕ_c)

Constrain Porosity from R - V_p Data Pair



●	Example data pair (R_{-ex}, $V_{p\text{-}ex}$)
$\phi_{ex\text{-}min}$	Minimum Porosity
$\phi_{ex\text{-}max}$	Maximum Porosity

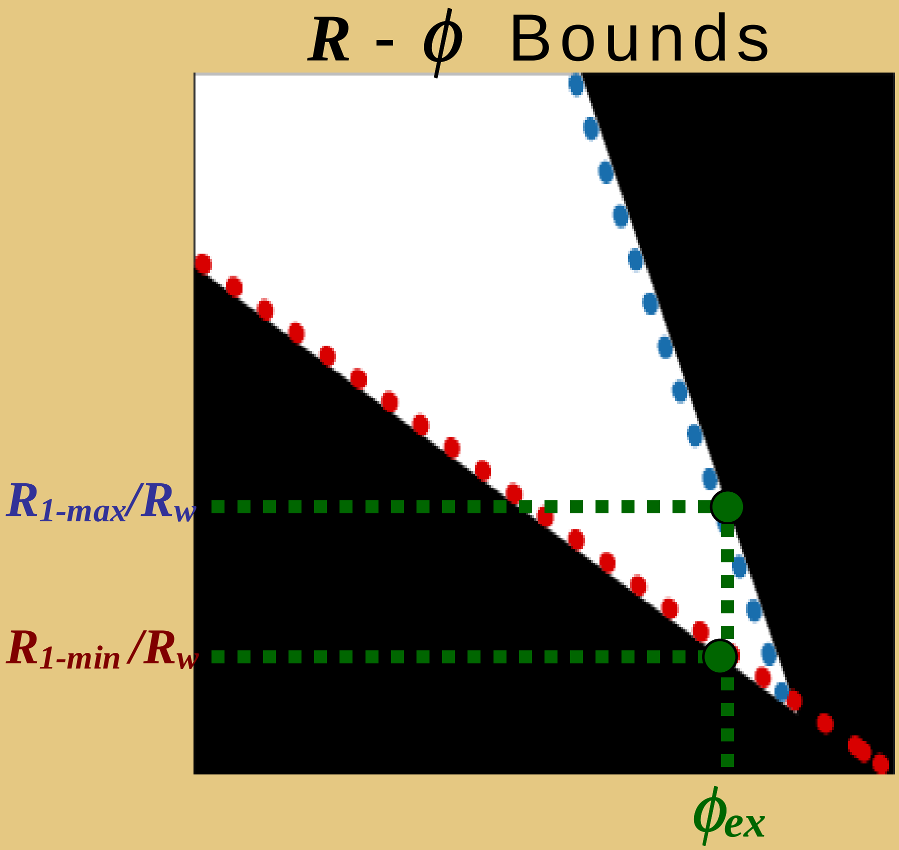
Application 2: Constraining R - V_p Pairs

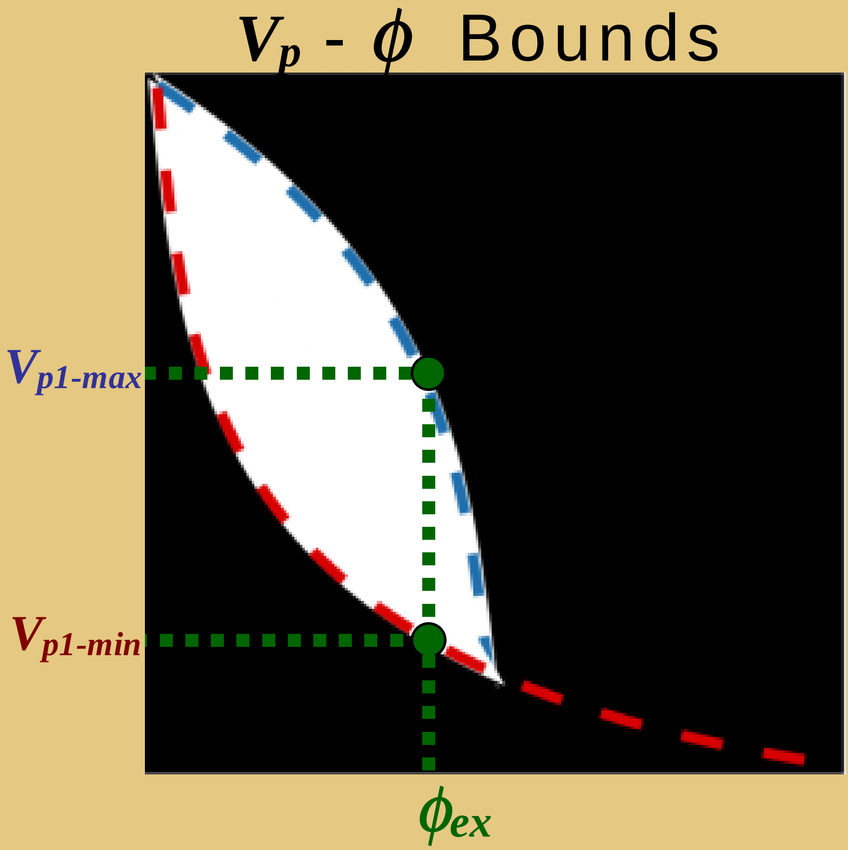
Data: Porosity (ϕ)

Parameters for Velocity Bounds:

- Bulk moduli (K_f, K_m)
- Shear moduli (μ_f, μ_m)
- Densities (ρ_f, ρ_m)
- (Optional) Critical porosity (ϕ_c)

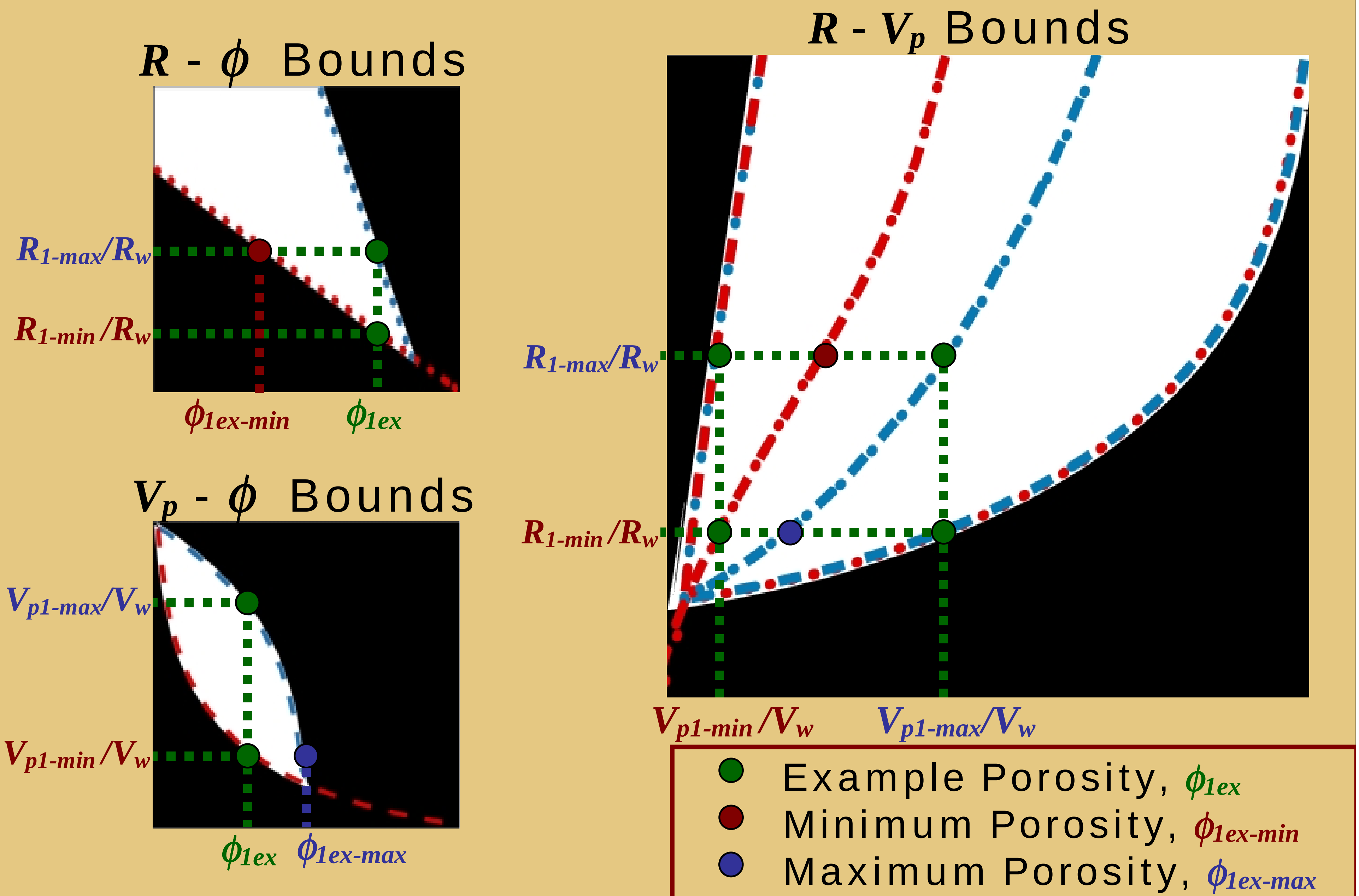
Constrain R - V_p from Porosity Data





● Example Porosity, ϕ_{ex}

Range in Porosity within R - V_p Bounds



Application 3: Diagnose Material Properties

Data:

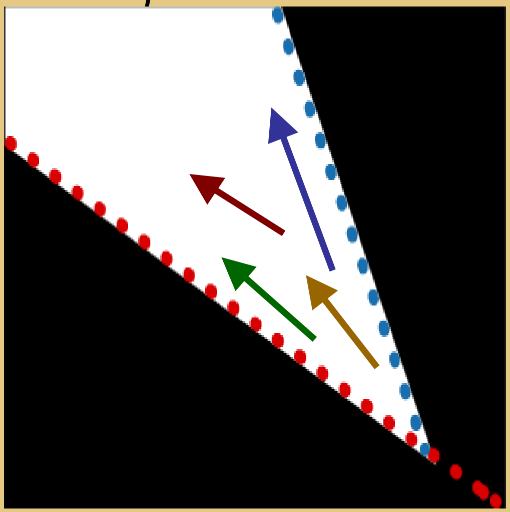
- Co-located resistivity - velocity (R, V_p) measurement
- Pore-fluid resistivity (R_w)

Parameters for Velocity Bounds:

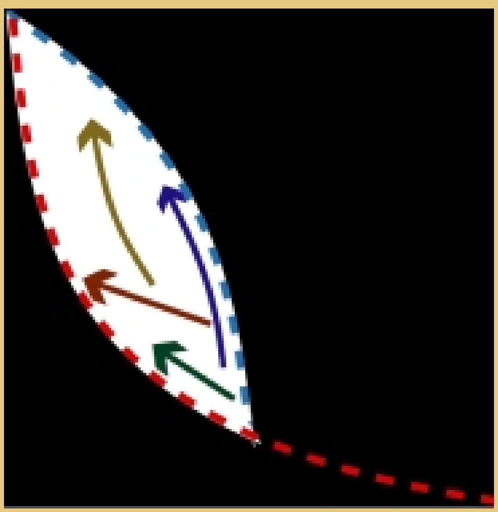
- Bulk moduli (K_f, K_m)
- Shear moduli (μ_f, μ_m)
- Densities (ρ_f, ρ_m)
- (Optional) Critical porosity (ϕ_c)

Trends within the R - V_p Bounds

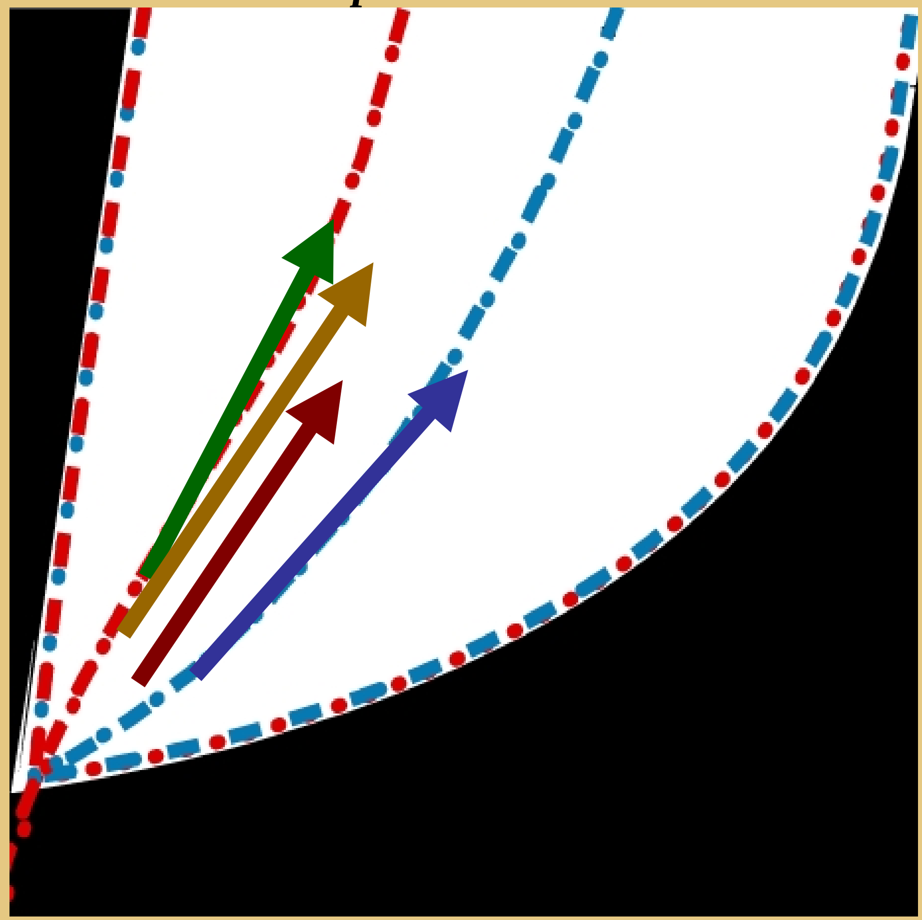
R - ϕ Bounds



V_p - ϕ Bounds



R - V_p Bounds



Significance of the R - V_p Relationship

Potential for using resistivity logs to constrain surface seismic interpretations.

Potential for integrating electrical and elastic theory and empirical relationships to characterize material properties.

Sediment Rock Physics Results

R - ϕ data for loose glass spheres fall along the lower HS resistivity bound.

Archie's equation with a=0.25, m=4 provides an empirical upper R - ϕ bound.

R - ϕ data for cemented glass spheres fall along the empirical upper bound. R - V_p bounds can be defined by upper and lower R - ϕ and V_p - ϕ bounds.

Porosity can be constrained using R - V_p data and respective bounds.

R - V_p estimates can be constrained using porosity data and R - V_p bounds.

Changes in lithology and flow properties between hydrogeologic units can be diagnosed using and R - V_p data and bounds.