Processing Large FORC Diagram Datasets applied to Earth-Science Research

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Outline

FORCs in the Earth Sciences
Quantitative use of FORC diagrams
Processing Large Datasets
Materials

Rocks
Sediments
Archeological artifacts
Meteorites
Sediments
bread and butter of FORCs

Mixture of magnetic minerals form a variety of sources
Goal: to determine components and interpret them

Messy, but...
Sediments
bread and butter of FORCs

...We kind of know what to expect
Magnetic minerals

- Magnetite: Fe$_3$O$_4$
- Hematite: Fe$_2$O$_3$
- Goethite: FeO(OH)
- Greigite: Fe$_3$S$_4$
Environmental magnetism

Interdisciplinary subject with applications in

Paleoclimate
Paleoceanography
Paleolimnology
Sediment Diagenesis
Iron Biomineralization
Archeology
Pollution
FORC Diagrams

N Atlantic sediment

\[ \rho (\text{Am}^2 \text{T}^{-2}) \]

\[ \times 10^{-3} \]
Magnetic fingerprinting
FORC diagrams – SD grains

Posfai et al. (2006)
Magnetic fingerprinting
FORC diagrams – PSD grains

\[ B_d (T) \]

\[ B_u (T) \]

\[ \rho (\text{Am}^2 \text{T}^{-2}) \]

Clay 0-4 \( \mu \text{m} \)
Magnetic fingerprinting
FORC diagrams – MD grains

\[ B_c (T) \]

\[ B_u (T) \]

\[ \rho (Am^2 T^{-2}) \]

coarse silt
40-63 µm

5 µm
Unmixing
tool that enables the quantification of magnetic components in sediments
Physical unmixing

clay and fine silt

fine-medium silt

medium-coarse silt
Chemical unmixing - dissolution

**pre-treatment**

**post-treatment**

Ludwig et al. 2013
Numerical unmixing

Using the entire FORC diagram to quantify the contribution of end member components
Principal Component Analysis

Multivariate technique that analyzes datasets for which observations, i.e. FORC values are described by several inter-correlated variables, i.e. pairs of \((B_c, B_u)\)
Principal Component Analysis

Represents data as a linear combination of a new set of uncorrelated variables, the principal components (PCs)

Lascu et al. 2015
G-cubed
Principal Component Analysis

![Reasonable image of a scatter plot with labeled axes and data points representing PC 1 and PC 2 scores. The plot shows a distribution of data points in a 2D space with labels for MD and PSD.]
Principal Component Analysis

Sample = PC1 Score x PC1 Loading + PC2 Score x PC2 Loading + error + Mean
Principal Component Analysis

Sample = PC1 Score x PC1 Loading + PC2 Score x PC2 Loading + error + Mean
Unmixing Model

Sample = f1 x EM1 + f2 x EM2 + f3 x EM3
End Members (EMs)

Sample = f_1 \times EM_1 + f_2 \times EM_2 + f_3 \times EM_3
End Members

Ideally comprise one component
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Physically realistic FORC diagram
End Members

Ideally comprise one component

Physically realistic FORC diagram

Interpretable in geological context
End Members

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Physically realistic FORC diagram

Interpretable in geological context

The more variability in the dataset, the better defined the bounds of the mixing space!
End-member variations control bulk environmental magnetic parameters

Channell et al., 2016
End-member variations describe climatic, oceanographic, etc., phenomena.

McCave et al. (1995)

Channell et al., 2016
Sortable silt analysis flowchart

1. **Sample Cores (approx. 10 cm²)**
   - **Subsample**: Approx 0.5 g
   - **Weigh**
   - **Freeze Dry**

2. **If Residue Contains > 5% Biogenic**
   - **Weigh**
   - **Gasometric Calculation (2 N HCl Solution)**
   - **Pretreatment (Wet)**
     - Digest organic matter (HCl / boil / wash)
     - Ultrasonic dispersion; Overnight agitation in 0.1% Calgon solution

3. **Remove Bio-Opal (2N NaOH Solution at 85°C for 3 hours)**
   - **Weigh**
   - **Gasometric Calculation (2 N HCl Solution)**
   - **SEDigraph #1**

4. **Bulk Sediment Carbonate Content**
   - **Subsample Pipette 0.5 g**
   - **Wet Sieve (60 μm)**
   - **SUBSAMPLE Toothpick**
   - **% Coarse Fraction Content; Derive: Co Fract % CaCO₃ Content (Forams)**
   - **Smear Slide Microscopic Examination**
   - **Fine Fraction Composition**
   - **Further Co.Fract. Studies (Forams counts, Stable isotope ratios, Cδδ/Cδδ ratios, etc.)**

5. **Remove CaCO₃ - Slow digestion in 1M Acetic acid soln**

6. **If Bio-Opal > 50%**
   - **Weigh**
   - **Gasometric Calculation**
   - **Tripe Wash (neutralise pH) Centrifuge**
   - **Remove Bio-Opal (2N NaOH Solution at 85°C for 3 hours)**

7. **Further Studies of Lithogenic Fine Fraction (e.g. XRD, XRF, Wet Chem)**

8. **If Bio-Opal < 5%**
   - **Weigh**
   - **Derive: Carbonate % (≤ C12/S1)**
   - **Fine-Fraction Size Distribution**

9. **If Bio-Opal < 5%**
   - **Weigh**
   - **Derive: < 10 μm, Carbonate % (≤ C12/S1)**
   - **Fine-Fraction Size Distribution**

10. **Derive: Carbonate (or Biogenic)**
    - **Non-Carbonate (or Lithogenic)**
    - **Fine Fraction Size Distribution**

McCave et al. (1995)
Summary

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PCA describes data objectively via its main modes of variability
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PCA space can be used as a canvas for unmixing.
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FORC diagrams provide a unique opportunity for fingerprinting domain states in natural samples.

PCA describes data objectively via its main modes of variability.

PCA space can be used as a canvas for unmixing.

FORC-PCA provides a fundamental level of understanding what controls bulk environmental magnetic parameters.
Goal

Create reference PCA sets based on canonical samples that represent the full range of domain states expected in specific geological settings.
Software

FORC environmental magnetism (FORCem) now part of FORCinel 3.0!

www.esc.cam.ac.uk/nanopaleomag

Lascu et al. 2015 G-cubed