Combining hyperspectral and XRF analyses to reconstruct high-resolution past flood frequency from lake sediments

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Introduction
Flood studies

- Flood records from lake sediment could be a proxy of paleo-hydrological variations
- Current increase of the number of studies using flood frequency and magnitude
- Building a flood chronicle is time consuming, and currently made using naked-eye observations

Wirth et al., 2013, QSR
T1 deposits = Turbidite-type • 148 deposits counted from naked-eye observations • mean thickness of 5.8 mm
Limitations of the classical methods

1. Destructive analyses
2. Time consuming
3. Low resolution (from naked-eye observations, grain-size, or spectrocolorimetry analyses)
4. Linked to the observer
5. Incertainty on the origin of the deposits (no systematic linked between proxys and turbidites)
6. Hard to detect the upper limit of each instantaneous deposits
Proposed methodology

- Based on two complementary sensors:
  - Visible and Near Infrared hyperspectral sensor: molecular composition
  - X-Ray fluorescence spectroscopy: elementary composition
- Validation with naked-eye observations
Study site

➢ Lake Le Bourget (LDB)
  ➢ Northern French Alps
  ➢ Length = 18 km
  ➢ Surface area = 44.5 km²
  ➢ Altitude = 231 m a.s.l
  ➢ Main tributary = Rhône
Study site

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Hyperspectral methodology

- Visual description of the core
  - Hyperspectral analyses
    - Detection of instantaneous events
      - Manual selection of zones corresponding to instantaneous events
      - Test and selection of the best detectors to detect instantaneous events
    - Creation of instantaneous events chronicle
      - Reliability of the Hyperspectral’s instantaneous events chronicle
  - Naked-eye chronicle
Classical RGB imaging

3 planes

Depth

Width

612 nm

546 nm

436 nm


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Hyperspectral imaging

3 planes

Depth

Width

612 nm

546 nm

436 nm

n planes

612 nm

546 nm

436 nm

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Hyperspectral sensor properties

- 2 hyperspectral sensors:
  - Visible and Near-Infrared (VNIR)
    - Spectral range: 400-1000 nm (resolution 12 nm)
    - Spatial resolution: 60 μm
    - Some chemical information registered: colorful oxydes, pigments
  - Short Wave-Infrared (SWIR)
    - Spectral range: 1000-2500 nm (resolution 6 nm)
    - Spatial resolution: 200 μm
    - Some chemical information registered: organic matter, hydrocarbons, mineral compounds, moisture
Machine learning for events classification

1. Events labelling
   - Continuous sedimentation
   - Instantaneous events

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Machine learning for events classification

1. Events labelling
2. Machine learning model estimation

- Decision tree (DT)
- Random forest (RF)
- Artificial Neural Network (ANN)
- Convolutional Neural Network (CNN)
- Linear Discriminant Analysis (LDA)
- Quadratic Discriminant Analysis (QDA)
- Partial Least Squares Discriminant Analysis (PLS-DA)

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Machine learning algorithms:
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Machine learning for events classification

1. Events labelling
2. Machine learning model estimation
3. Model use on all the pixel of the hyperspectral image

**Machine learning algorithms:**
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VNIR classification maps

- VNIR highly sensitive to surface and illumination defects
- Misclassification with non-learning deposits (laminae)
SWIR not sensitive to the previous defects
Comparison with classical images

- Optimal model: SWIR + PLS-DA

Laminated Illumination defects
Estimation of the HSI chronicle (thresholds)

Thin (<50%):
✓ Thin deposits
✗ Artifacts / misclassifications
✗ Wrong limits:
  ✗ Combination of close deposits
  ✗ Due to the curvature of the deposit

Large (>50%):
✓ Artifacts / misclassifications
✗ Thin deposits
~ Wrong limits due to the curvature of the deposit

1) Average (50%),
2) Large (>50%) for large ones:
✓ Thin deposits
✓ Artifacts / misclassifications
~ Wrong limits due to the curvature of the deposit
Comparison of the chronicles

- **Flood naked-eye** vs HSI **instantaneous event** chronicles

**Lamina area**: difficult to studied by naked-eye

- **N_{ref} = 51**
- **N_{HSI} = 86**
- **r = 0.86** SE = 3.04

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Color differences closer: difficult to identify by naked-eye
Complementary information

- Matlab codes will be available soon

- Spectral preprocessing need to be used to reduce noise and highlight discriminant information

- Conclusions on the use of the methodology on several cores:
  - SWIR sensor has higher discriminant capacities, but not enough to characterize instantaneous event types
  - VNIR sensor sensible to surface defects and illumination
  - Models are site-specific

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X-Ray fluorescence methodology

- High-resolution XRF analyses
- Understanding of lake mechanics
  - Notions about the physics in the studied lake
  - XRF trend along the core and PCA
  - Comparision with other results (SEM, EDX, XRD, etc.)
- Selections of proxy of floods
  - Terrigeneous elements to trace detrital inputs
  - Mn or Mn/Fe to trace oxygenation of bottom waters
  - Zr/K to trace grain-size variations
X-Ray fluorescence properties

- Avaatech core scanner
  - Spatial resolution: 500 μm
  - Two runs:
    - 10 kV and 0.25 mA for 20 s to detect lightweight elements
    - 30 kV and 0.4 mA for 20 s
  - Registration of the chemical éléments
Selection of flood proxies

- From XRF and SEM+EDX
Selection of flood proxies

- From XRF and SEM+EDX
Selection of flood proxies

- Mn : proxy of oxygenation of the water at the sediment interface

- Ti : proxy of terrigenous input of the river

- Mn+Ti : flood origin bringing terrigenous particles and well oxygenated water to the water’s-sediment interface
Combining hyperspectral and XRF analyses

Visual description of the core

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Naked-eye chronicle

Creation of interpreted flood events chronicle

Flood chronicle + intensities (thickness)
Proxies comparison

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XRF use alone?

- Ti signal too noisy
- For both proxies, there are many peaks independent of flood signatures
- Only the combination of the two sensors can characterize the flood layers
Event characterization

- Combination of HSI instantaneous events + XRF proxies
Comparison of chronicles

Flood naked-eye vs HSI+XRF flood event chronicles

- Lamina area: difficult to studied by naked-eye

- Color differences closer: difficult to identify by naked-eye

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Distribution analysis

- Agreement between both depth distribution

- Linear trend between the thickness distribution, but with higher values estimated by HSI+XRF
  - curvature of the deposits => bias on the layer limits
  - eye resolution => highest HSI sensibility
Conclusion

- HSI + machine learning algorithm allows to estimate instantaneous layers

- + XRF proxies => flood can be characterized

- Instantaneous and flood chronicles can be estimated at a 200 µm resolution

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Perspectives

- Discrimination of several sedimentary processes (instantaneous event types, or lamination)

- Combining some complementary sensors

- Transfer to other samples
Hyperspectral imaging an efficient tool for multi-proxy estimations and sediment lithology descriptions to reconstruct paleoenvironment and paleoclimate at high-resolution.