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Hydrogeological assessment of a deep-seated coastal landslide based on a multi-disciplinary approach (Villerville, Normandy)

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I Study area and issues

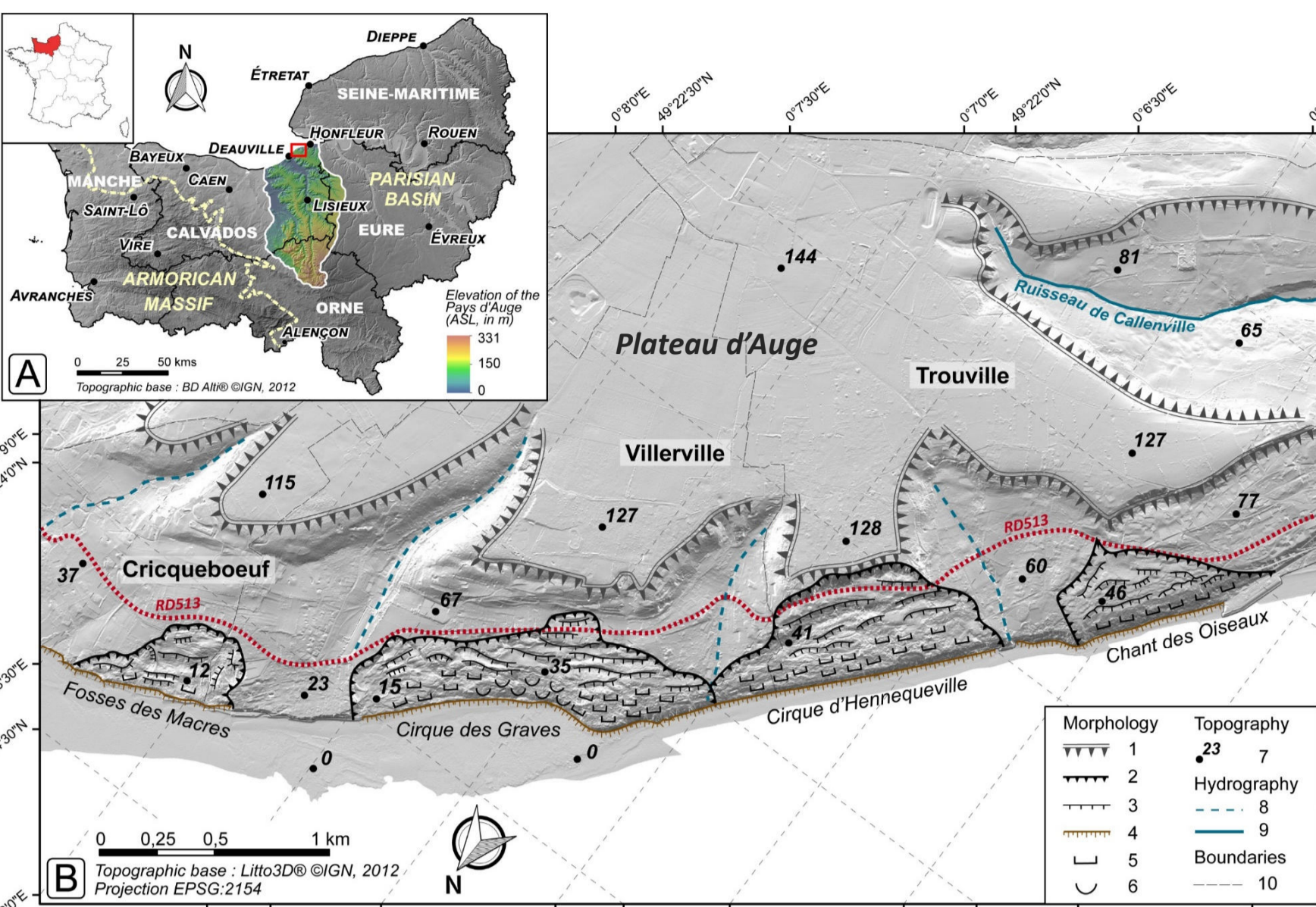


Fig. 1 - A: Location of the study field in Normandy; B: Morphological sketch of the four major coastal landslides of the Pays d'Auge, between Deauville and Honfleur. 1. Border of the Plateau d'Auge; 2. Main scarp of the landslides; 3. Secondary scarp; 4. Basal scarp; 5. Bumpy morphology; 6. Solifluction lobes morphology; 7. Spot height; 8. Temporary river flow; 9. Permanent river flow; 10. Municipality boundary.

The purposes of this study are :

- (1) Improve the **general hydrogeological knowledge** on the landslide functioning ;
- (2) Determine the **main water paths** at the slope scale ;
- (3) Identify the **major discharge areas** of the continental groundwater (from the Plateau d'Auge).



Fig. 2 - Destroyed building by the acceleration of January 1982 (Maquaire, 1985)

Located in the Pays d'Auge (Normandy), the Cirque des Graves is a **rotational-translational landslide** (Fig. 1) with **multiple nested slip surfaces**. It has an area of 47 hectares (450 m width x 1,600 m length). From top to bottom, the **stratigraphy is composed by 5 layers** : (i) Cenomanian chalk and glauconite; (ii) Albian clay and sands; (iii) Kimmeridgian clays & marls; (iv) Oxfordian marls; and (v) Upper-oxfordian sandstone (Fig. 3).

This landslide is characterized by :

- A **continuous spreading** due to local readjustments (2 to 10 cm.yr) ;
- Intermittent accelerations (Fig. 2) with **retrogressive dynamics** (e.g. 1982, 1989, 1995 & 2001) ;
- A **hydrologically-driven activity** (relation rainfall-groundwater-displacements).
- **Multiple water inputs** (2 water tables + impluvium) and complex flows.

II Methodology

We used 3 approaches with heterogeneous datasets (old and new) to set the hydrogeological mechanisms :

- (1) **Geomorphological and geological appraisal** (i.e. boreholes and geomorphological features) (Fig 4A) ;
- (2) **Hydrological appraisal** (i.e. physico-chemical analysis and piezometric chronicles) (Fig 4B) ;
- (3) **Geophysical appraisal** (i.e. electrical resistivity tomography and self-potential surveys) (Fig 4C).

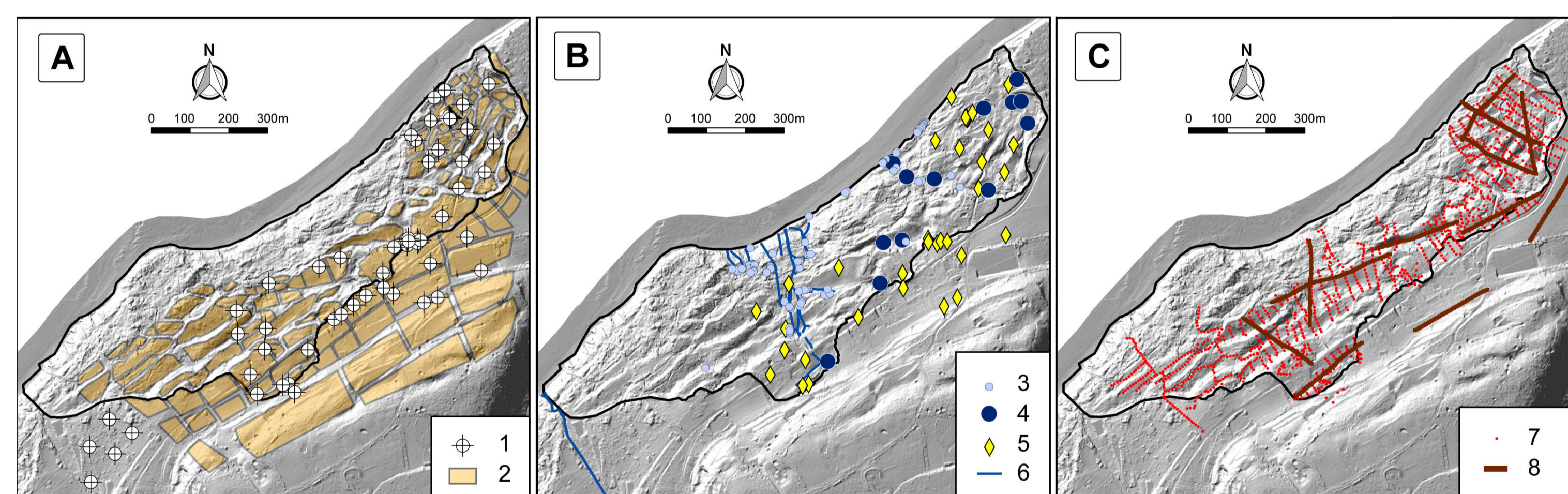


Fig. 4 - Type and spatial distribution of the data used for the (A) morphostructural approach, (B) hydrological approach and (C) geophysical approach. 1. Drilling; 2. Chalk compartment delineation (from Lissak, 2012); 3. Spring; 4. Pond; 5. Piezometric measurement (single or continuous); 6. Drainage network; 7. SP measurement (2018); 8. ERT profile.

III Landforms and structural predispositions

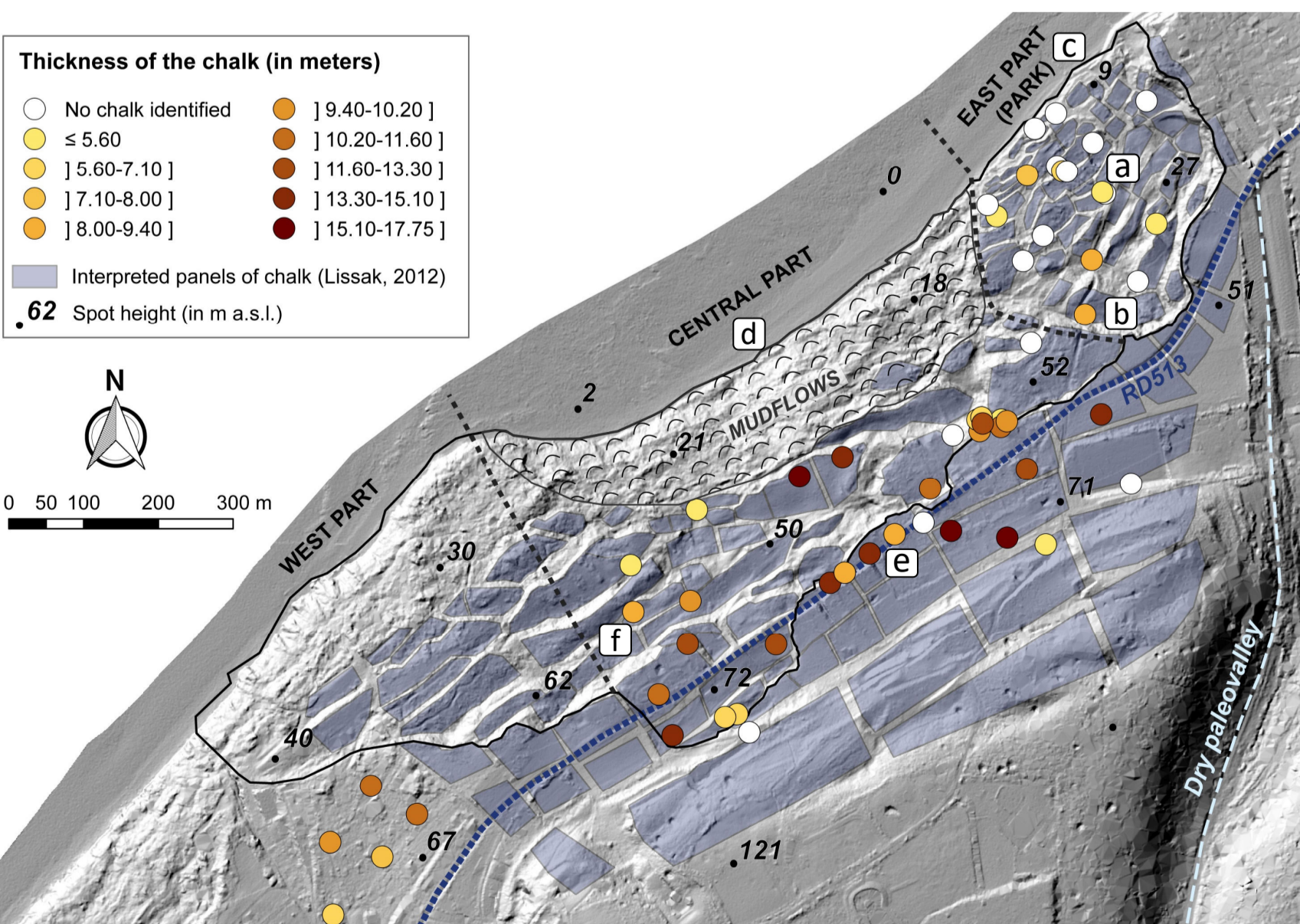


Fig. 5 - Thickness variation of the chalk from borehole logs in or nearby the Cirque des Graves and geometry of the identified panels by Lissak, 2012

- **Hummocky and complex geomorphology** (Fig. 6) which facilitate both water seepage (cracks and fracture porosity) or stagnation (clayey surficial formations, scarps & counter-scarps) ;
- **Thinner chalk** in the east and west borders, and **particularly in the park** (eastern extremity), with smaller chalk panels. Chalk is thicker (10-17 m) in the upstream central area (Fig. 5).



Fig. 6 - Main geomorphological features encountered in the Cirque des Graves (location given in Fig. 4). (a) Minor scarps and stairs morphology; (b) Main scarp of the cirque (chalk outcrop); (c) Heads (reworked formations) at the foot of the landslide; (d) Mudflows in Oxfordian marls on the coastline; (e) Recent crack on the RD513; (f) Building near a major scarp in the middle of the slide

IV Hydrological analysis

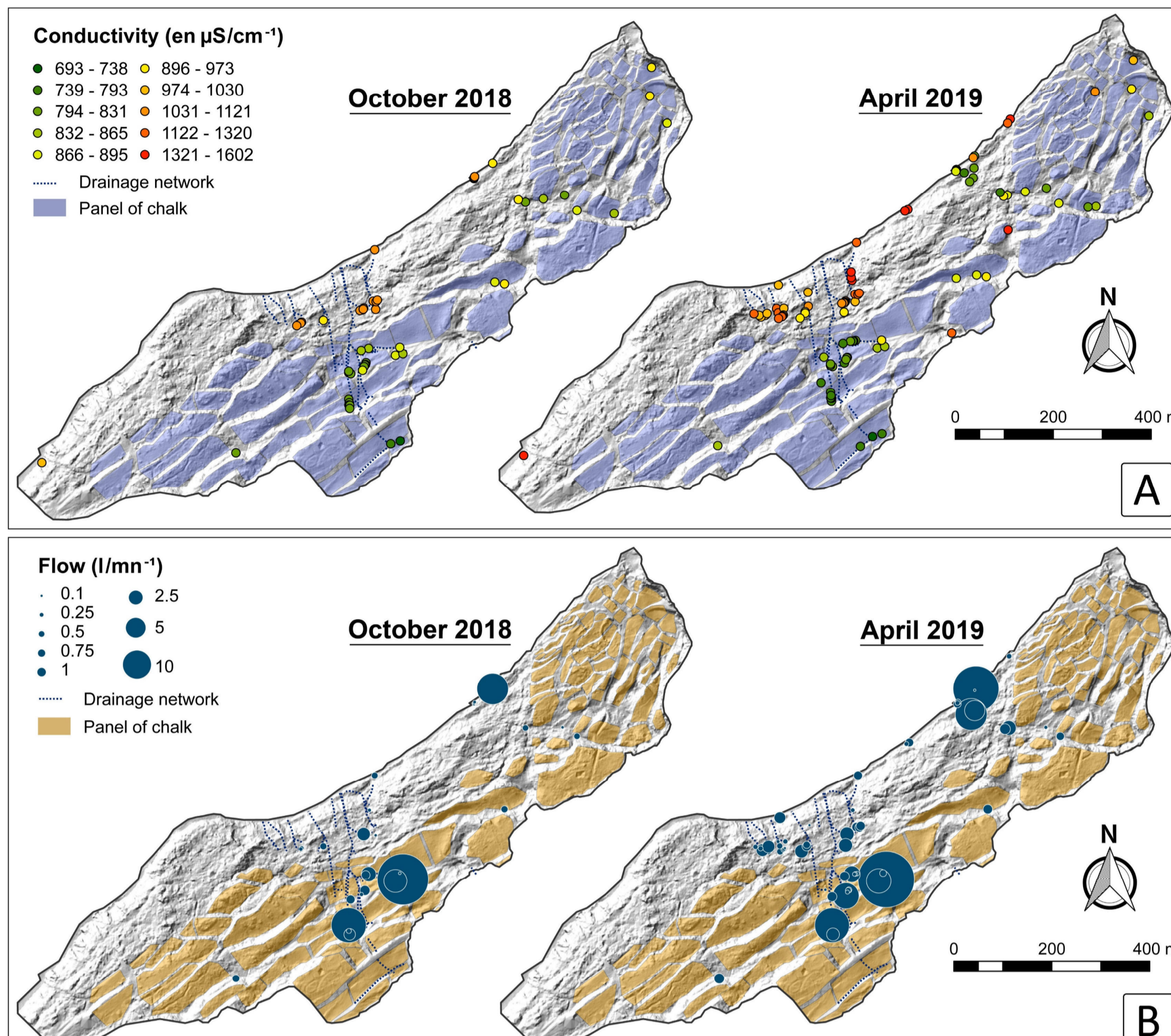


Fig. 7 - (A) Conductivity measured in springs, ponds, and drains and (B) water flow measured in natural springs at the Cirque des Graves during the field campaigns of October 2018 and April 2019

Measurements	October 2018	April 2019
Number of flowing springs	47	72
Number of ponds with stagnant water	8	13
Number of flowing drains	7	11
Temperature range (in °C)	12.0-20.3	9.3-17.7
Conductivity range (in µS.cm ⁻¹)	711-1103	693-1602
pH index range	6.68-8.55	7.19-8.58
Mean measured flow (L.mn ⁻¹)	2.52	2.59
Total measured flow (L.mn ⁻¹)	109.75	172.47

Tab. 1 - Compared results from the physicochemical campaigns of October 2018 (low waters) and April 2019 (high waters).

V Flow dynamics assessment from geophysics

- **Resistivity decrease in the north-east direction** linked with chalk condition and topography (Fig. 8) ;
- **GW flow probably mixed-up in the east** (weakest ρ values = thin and weathered chalk).

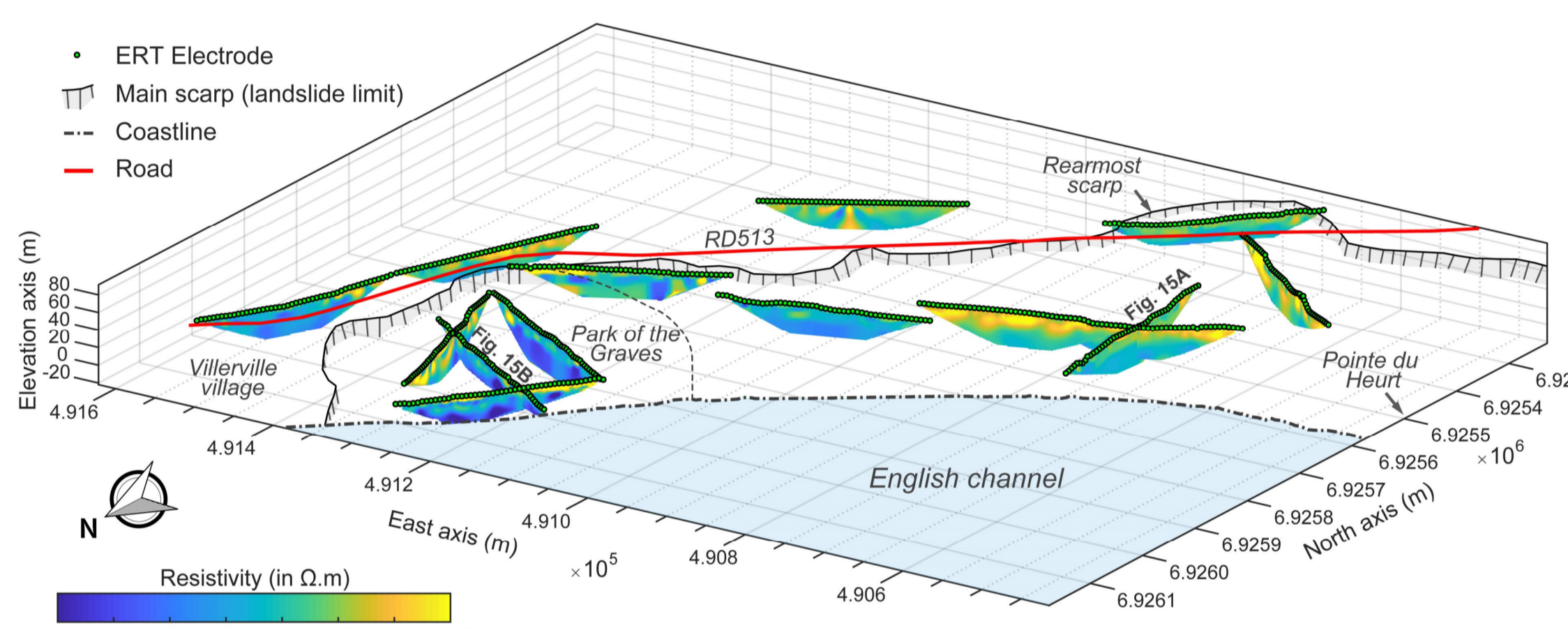


Fig. 8 - ERT (electrical resistivity tomography) profiles from the SISCA geophysical campaign (2008)

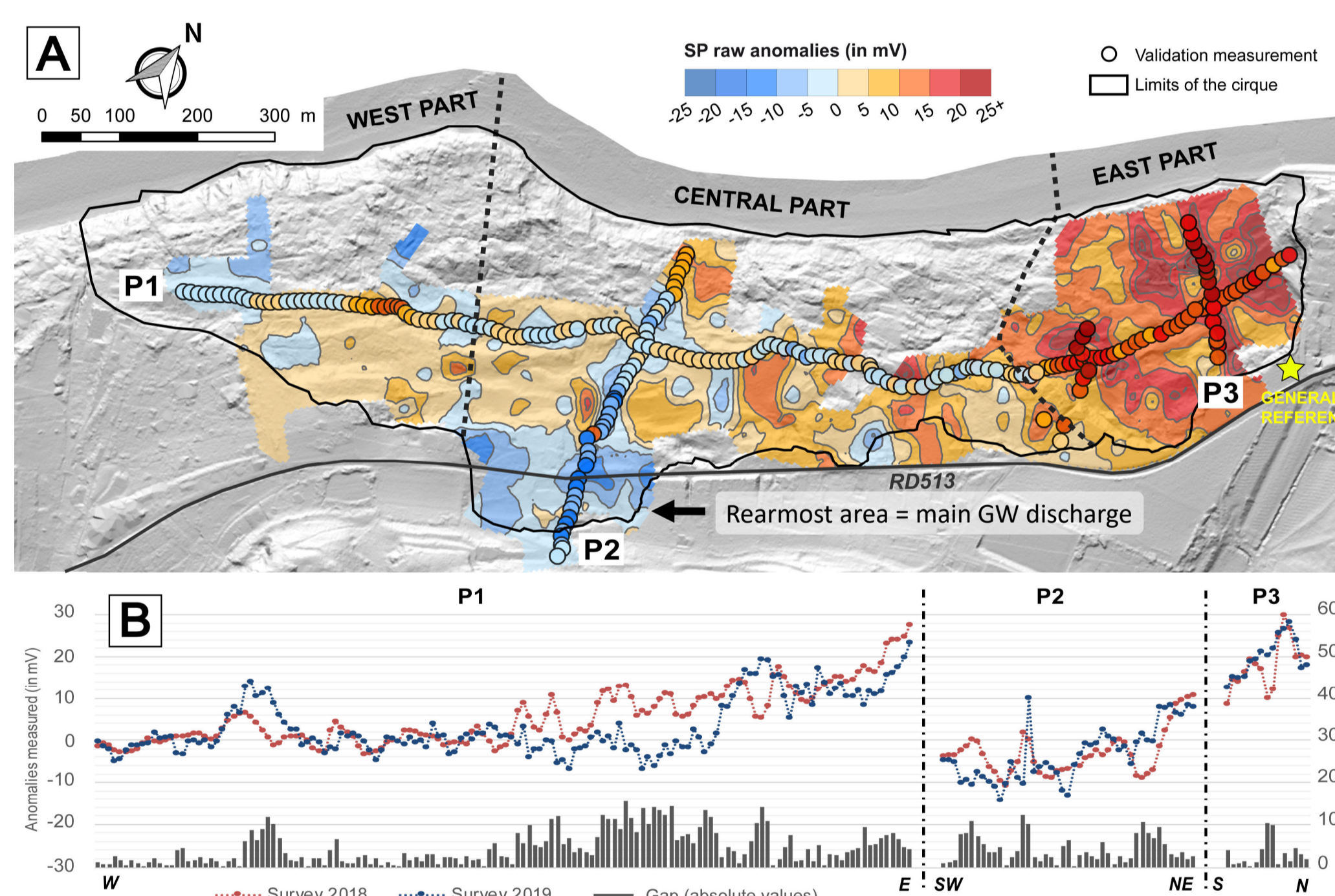


Fig. 9 - (A) Self-potential anomalies measurements from the 2018 survey (color map) and validation survey of 2019 (data points); (B) Assessment of the uncertainty and comparison between the surveys

- **Good correlation between ERT and SP :**

- **Central area** (Fig 10A) :

- ✓ Negative SP anomalies on slope breaks (downward waterflows following slip surfaces) correlated with strongest p values ;
- ✓ Positive SP anomalies correlated with springs and water accumulation (upward waterflows) and lower p clusters (saturation).

- **Eastern area** (Fig 10B) :

- ✓ Weak resistive thickness in surface (thinner and reworked chalk) ;
- ✓ Strong positive SP anomalies which underlines a parallel or upwards flow (no significant sinking of water).

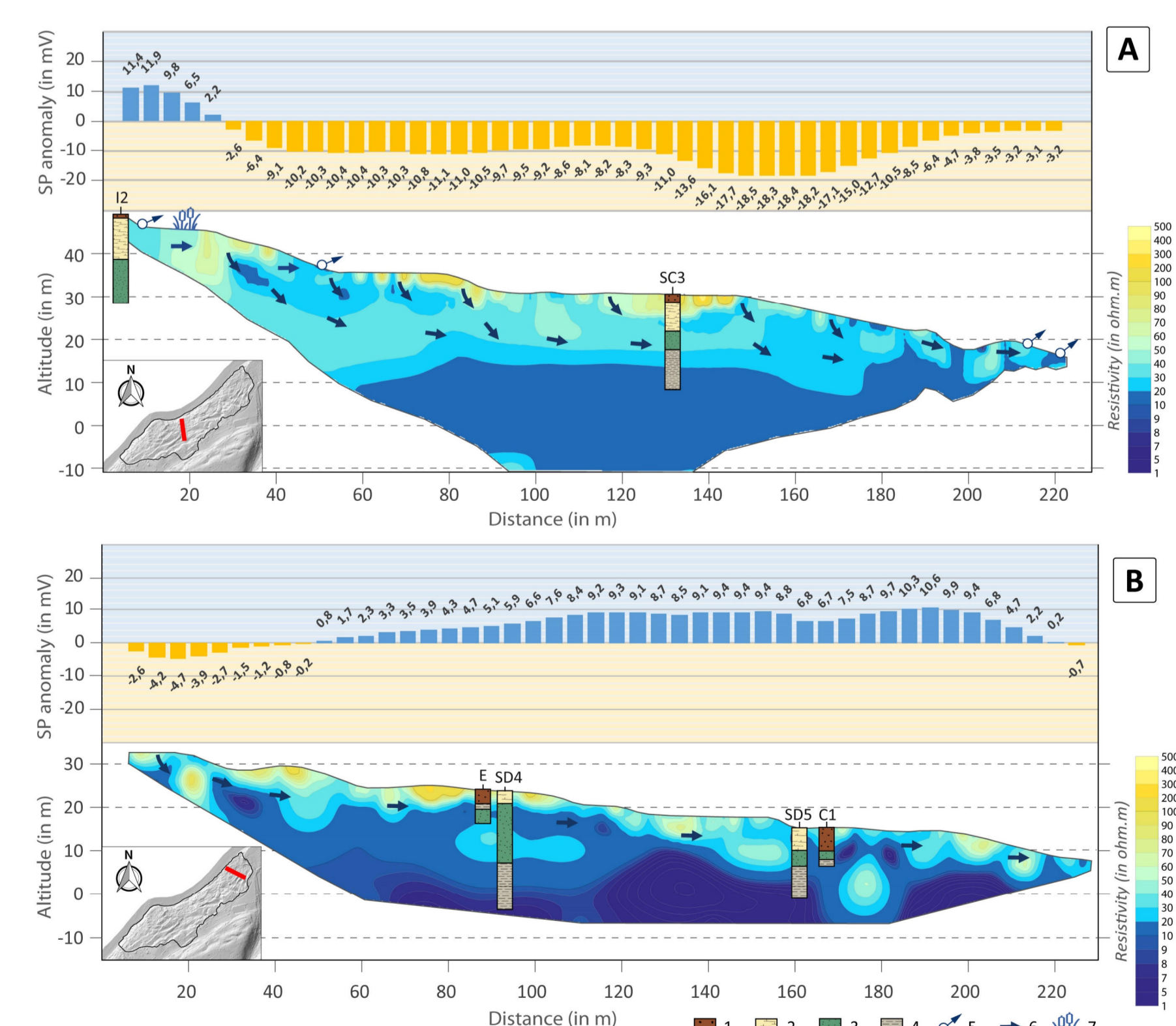


Fig. 10 - Comparison between the SP survey (2018) and the resistivity gradients from the ERT survey during the SISCA project (2007-2008) at (A) the middle-west part of the Cirque and (B) the east part of the Cirque (park)

VI Conclusions

- (1) The main discharge from the continental GW is at the **rearmost zone** of the main scarp (Fig. 9) ;
- (2) Division of the hydrogeological behaviour in **three compartments** :
 - ✓ **Eastern part** : shallow waterflow in heterogeneous matrix, parallel flow (undifferentiated GW) ;
 - ✓ **Central part** : partially splitted flow between chalk and sands GW's, with permeabilities (downward flow identified) and a continental discharge throughout the year (numerous permanent springs) ;
 - ✓ **Western part** : less data but probable deeper functioning (few springs, high scarps, large chalk panels).