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Contribution of thermal infrared images on the understanding of the subsurface hydrology.

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Introduction

High temporal resolution of space-based thermal infrared (TIR) images from for example METEOSAT and MODIS, along with the development of field TIR cameras, have permitted the increasing use of thermal remote sensing in Earth Sciences. More particularly in this domain, characterisation and understanding of the local and regional water cycle is primordial in the context of climate change, and TIR data may provide valuable information.

Consequently, our presentation highlights the role of subsurface fluid flows on the surface temperature dynamics that are controlled by permeability changes in the few meters of the undersaturated zone.

Surface temperatures are controlled by:

- physico-chemical properties of the surface (thermal inertia, albedo...);
- solar radiation;
- meteorological parameters (evaporation, rainfall, clouds);
- topography (sunny vs shadowed area).

When a temperature excess or loss is not controlled by none of these factors, we consider it as a thermal anomaly.

Why and how ?

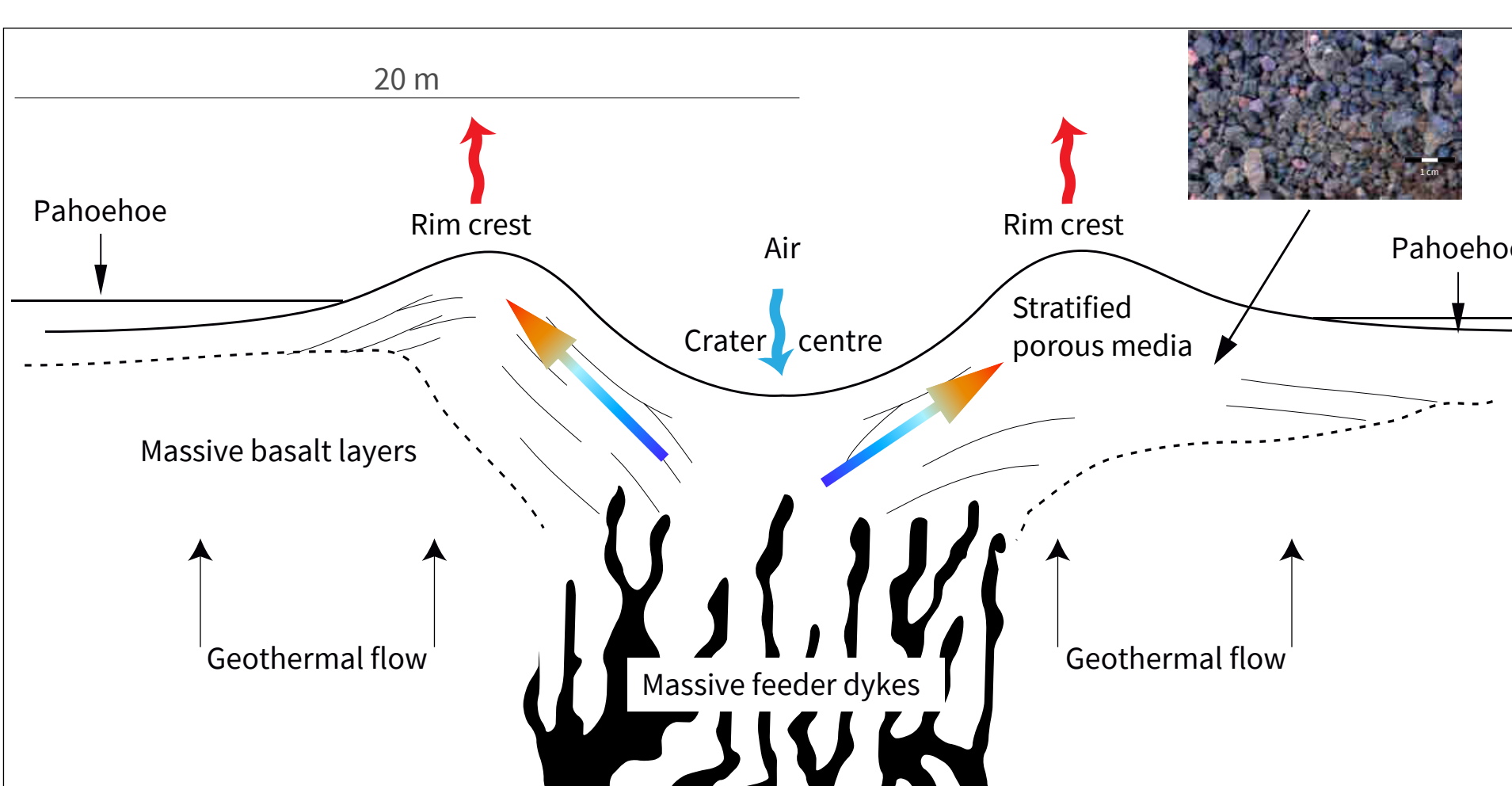
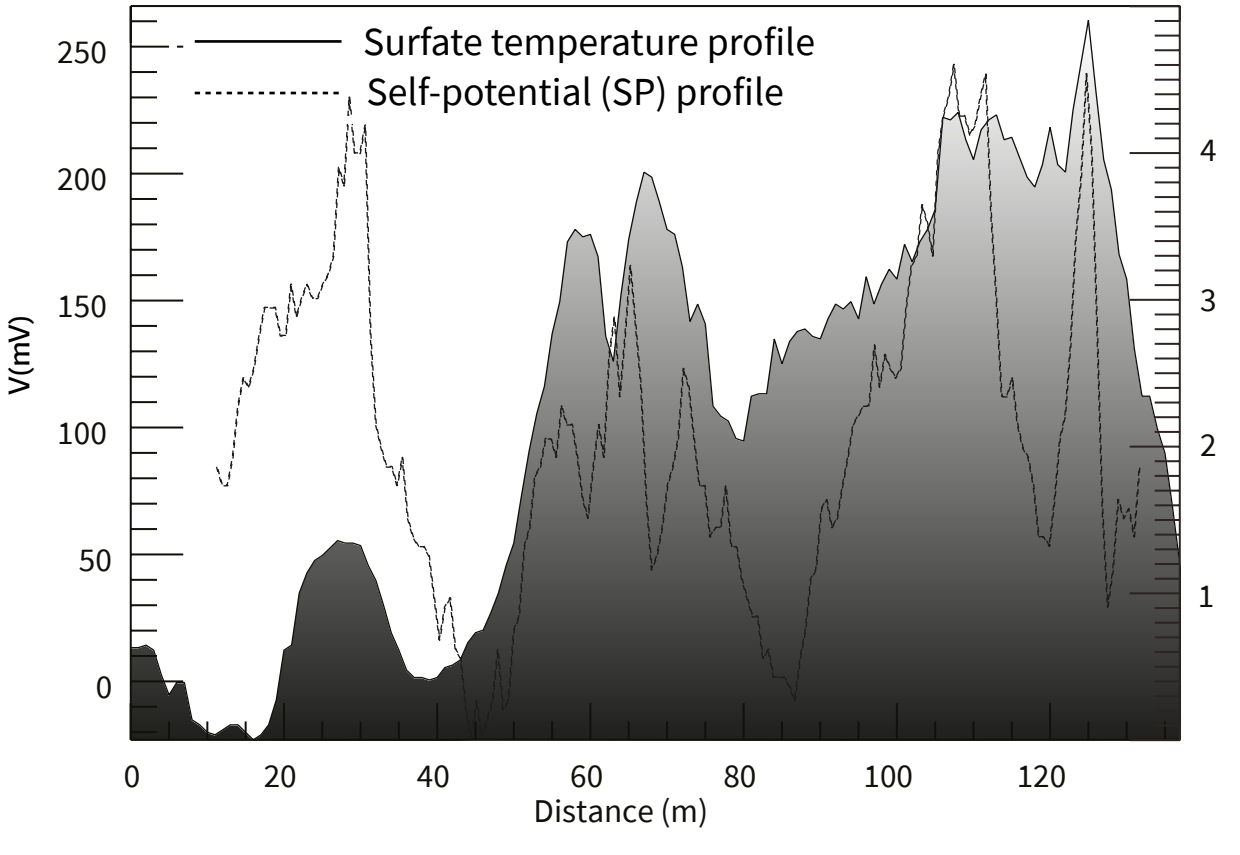
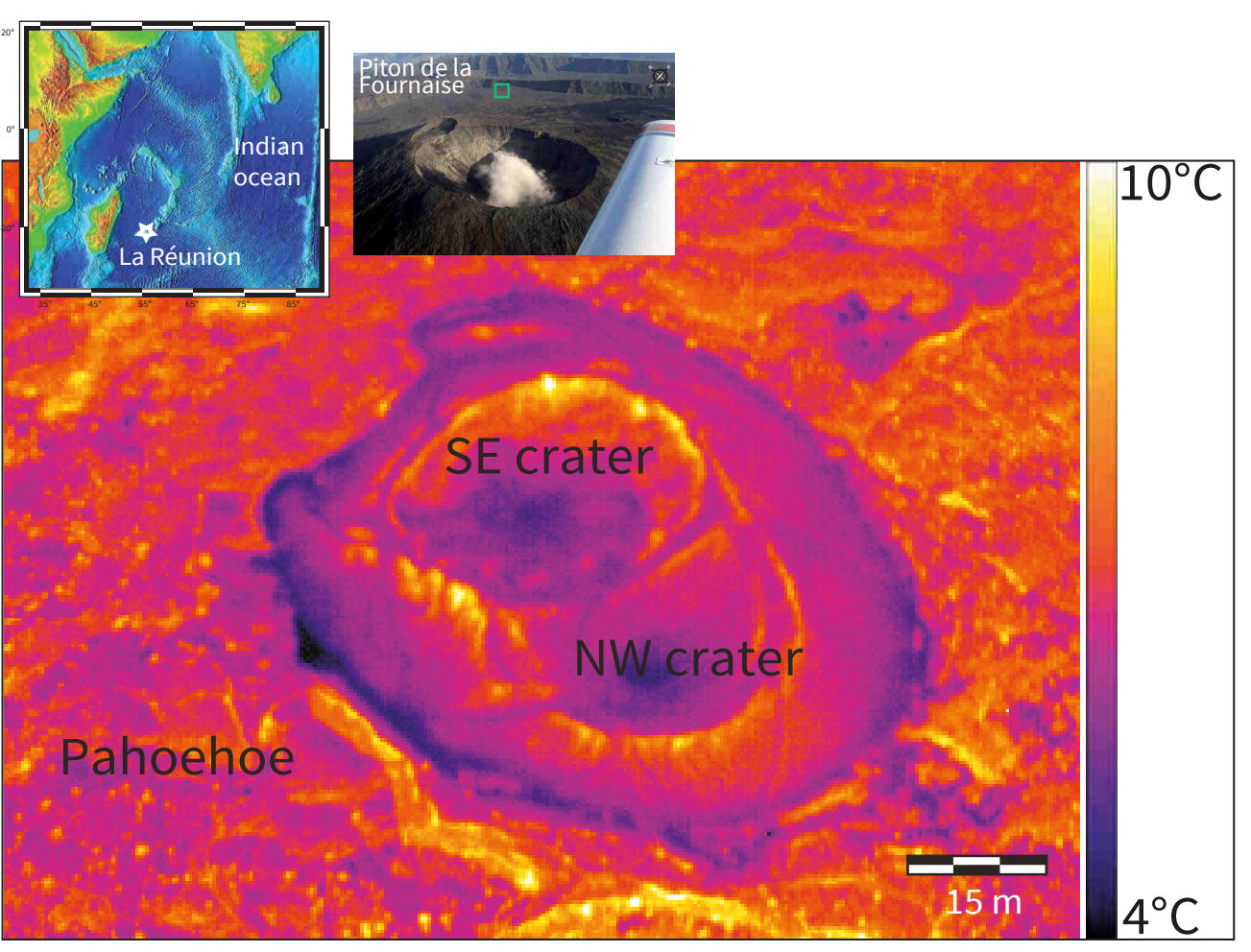
Considering these limitations, three examples (A to C) show the added value of the TIR methodology to understand the subsurface hydrology dynamics at multiple spatial and temporal scales.

This methodology relies on the use of temporal observations of surface temperatures. Such approach is particularly useful to detect weak temperature contrasts between 2°C and 10°C.

Thermal anomalies at a decametric scale

A. Characterisation of aerothermal processes within active volcanoes

The Formica Léo inactive cone is formed by lapillis and aggregates ($K = 3 \cdot 10^{-8}$ to 10^{-5} m^2) directly laying over massive basalts ($K \sim 3 \cdot 10^{-5} \text{ m}^2$).



In volcanology, TIR data are usually used to detect important temperature contrasts (60°C) linked to hot water flow within hydrothermal systems. The studies presented here [1; 2] show that field and airborne thermal sensors can help to characterise weak thermal contrasts (2° to 10°C) associated to subsurface airflow when combined with geophysical observations (here self-potentials). The impact on volcanoes of such "aerothermal systems" is the extraction between eruptions of an important amount of energy, estimated around several hundreds of mW m^{-2} .

Topography and conductivity contrasts are unable to explain the observed thermal difference of 4 to 5° between the rims of both craters and their centres.

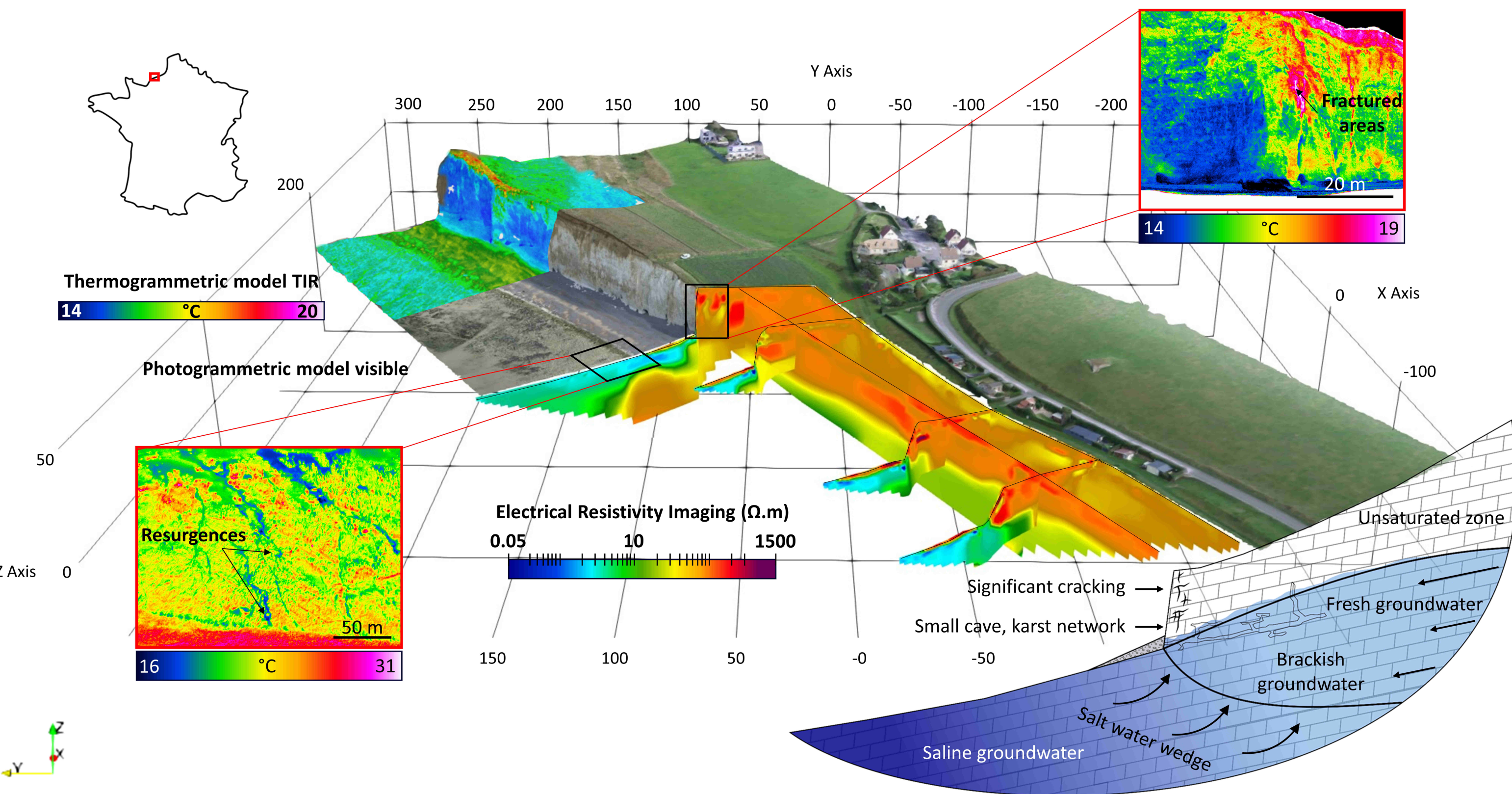
Self-Potential (SP) in situ measurements (water films movement on the porous matrix) of both craters are correlated with the thermal anomaly.

$$Ra_{eq} = \gamma \frac{\rho_0 g \alpha \Delta T H K}{\mu \kappa}$$

$$\gamma = \frac{\rho_a c_a n}{\rho_s c_s (1-n)}$$

Thermal anomalies at a pluri-kilometric scale

B. The role of hydrology in coastal retreat of chalk cliffs

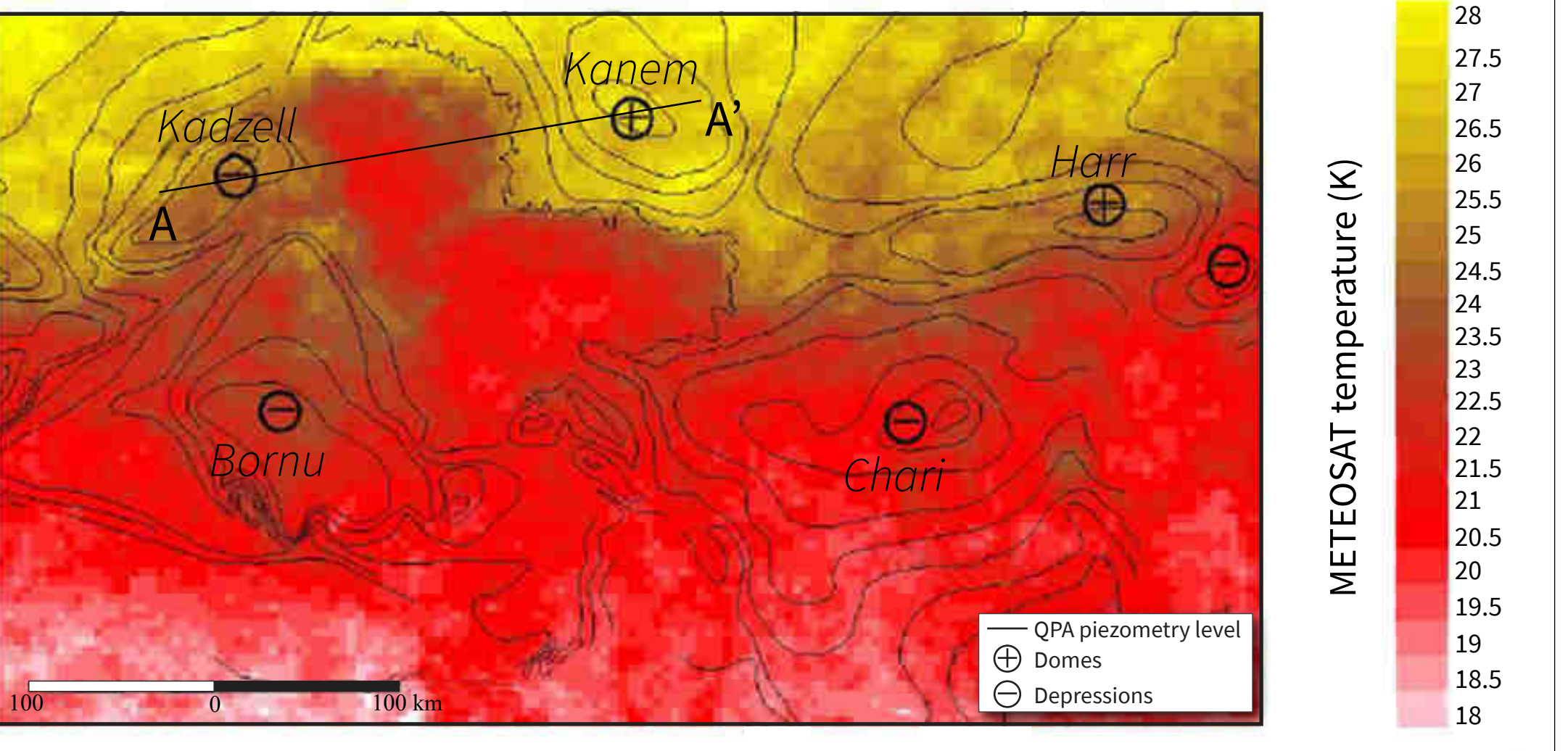


The understanding of the role of marine/coastal waters is promordial in coastal retreat research. The aim of the Defhy3geo regional project (2022-2025) is to characterize subsurface flow within the chalky cliffs of Sainte-Marguerite-sur-Mer (Normandy, France). For the first time, 3D TIR data obtained by drone combined with 3D electric imagery help to assess the interplay between marine and continental water within the cliff. TIR data are particularly useful to detect fractured zones and brakish water resurgences on the carbonated platform [3; 4].

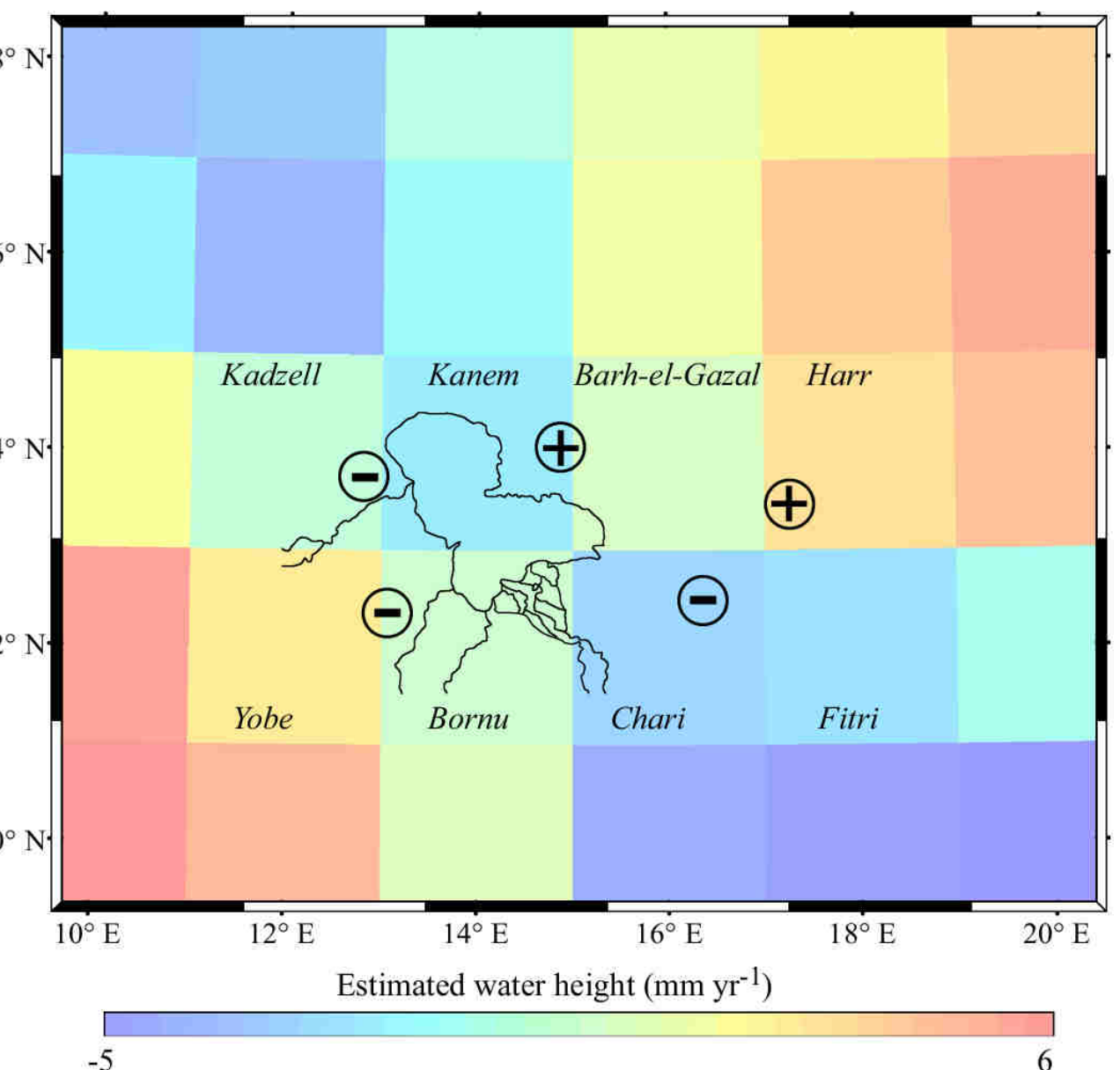
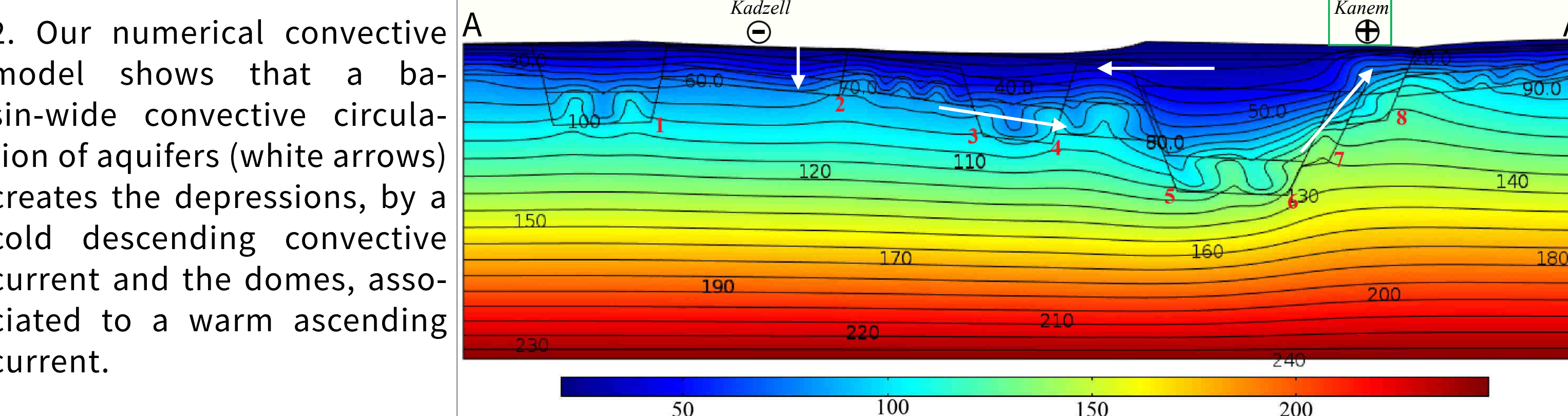
Take aways:

- The role of the convecting ascending current is to provide water at the surface and to maintain a minimal rate of humidity whatever the season.
- From nearly ten years, our studies demonstrate the capacity of TIR images to indirectly detect the fluids convective circulation and lateral heterogeneities of the surface permeability.
- This understanding had only been possible in using a broad and complete approach combining several observations and numerical modelling.
- This methodology now permits to better understand the exchanges between the subsurface and the atmosphere and can also be applied on different studies as leaks detection on dykes or landslides hydrology.

C. Characterisation of water resources in a sedimentary basin : application to the Lake Chad basin



1. The Quaternary Phreatic Aquifer (QPA) piezometry, characterized by large piezometric anomalies, show a correlation with surface temperature. Indeed, at the same latitude, domes are ~4-5 K warmer than the depressions [5].



In the Lake Chad basin, a correlation exists between piezometric levels and surface temperatures [5]. Using numerical simulations of fluid flow in porous media, we explain this observation by a basin-wide deep convective water flow bringing heat to the surface and inducing up to 10°C temperature contrast [6]. In this basin, uses of different satellite estimations as TIR and GRACE data help to constrain the spatial variations and the evolution of deep hydrogeological phenomena in (semi-)arid areas.

Perspectives:

- The future TIR missions as Trishna and the Copernicus LST will provide for the first time high-temporal and -spatial resolution surface temperatures that will permit to better understand the local and water regional exchanges.
- At large scale: actual TIR images and the future ones will provided interesting information on many geophysical domains as earthquakes studies.
- At small scale: UAV-based TIR images are particularly useful to cover kilometric and/or inaccessible areas.

References: [1] Antoine et al. (2009) J. Volcanol. Geotherm. Res. doi:10.1016/j.jvolgeores.2008.12.003; [2] Antoine et al. (2017) Geothermics doi:10.1016/j.geothermics.2016.01.003; [3] Junique et al. submitted to Journal of Hydrology; [4] Junique et al. (2023) Characteristics of saltwater wedge under the chalk cliffs of Sainte-Marguerite-sur-Mer (Normandy, France) using optical and geophysical methods, EGU conference; [5] Leblanc et al. (2003) Geophys. Res. Lett. doi:10.1029/2003GL018094; [6] Lopez et al. (2016) Surv. Geophys. doi:10.1007/s10712-016-9363-5