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Monitoring aquifers and subsidence with the chronometric leveling

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Overview

Subsidence poses a considerable threat to the sustainability and economic advancement of at least one-fifth of the world's population (Herrera-García, 2021). This challenge is especially pronounced in coastal and heavily urbanized regions, where ground subsidence rates of several centimeters per month or several meters per decade are observed. The origins of subsidence can be either natural or anthropogenic. It is predominantly influenced by the hydrological, geological, and tectonic characteristics of the region, as well as the geotechnical properties of the underlying formations. This study aims to evaluate whether chronometric leveling, conducted in France, can complement gravimetric, spatial imaging, and traditional leveling techniques for investigating vertical soil displacements. These displacements result from disturbances in groundwater resources, which are monitored using piezometers, and can arise from climatic or anthropogenic factors.

Chronometric leveling and aquifers

The study is part of the ANR ROYIMAGE project, which aims to develop a transportable ytterbium (Yb) optical lattice clock with a relative frequency uncertainty of 10^{-18} . Connected to the nodes of the REFIMEVE fiber network, the clock will enable remote clock comparisons for conducting chronometric geodesy and geoscience applications.

Chronometric leveling

Gravitational redshift → General relativity predicts that time flows differently for clocks placed in different gravitational potentials

→ Clock comparisons can measure directly geopotential (not directly available with traditional techniques) and height differences

Clock frequency shift
 $\Delta f/f = 10^{-17} (-18)$

Geopotential variations
 $\Delta W \approx 1 (0.1) \text{ m}^2/\text{s}^2$

Height variations
 $\Delta H \approx 10 (1) \text{ cm}$

$$\frac{\Delta f}{f_p} = \frac{f_Q - f_p}{f_p} = -\frac{W_p - W_Q}{c^2} + o(c^{-4}) \approx -\frac{\Delta W}{c^2}$$

$$\Delta W = C_Q - C_p = \bar{g}_Q H_Q - \bar{g}_p H_p \approx \bar{g}_p (H_Q - H_p) \approx \bar{g}_p \Delta H$$

$C_p = W_0 - W_p \rightarrow$ Geopotential number $\bar{g}_p \rightarrow$ Mean gravity
 $H_p = C_p / \bar{g}_p \rightarrow$ Orthometric altitude

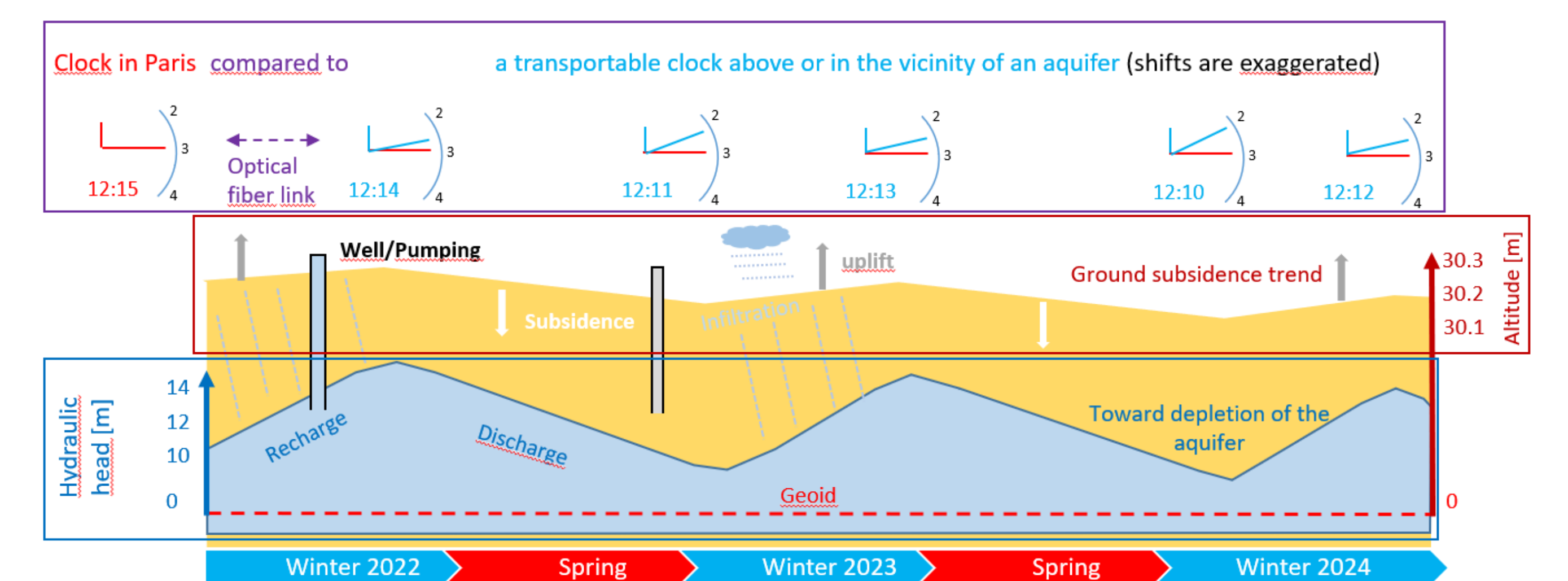
Altitude difference effect

Reference clock Field clock at different H

Mass variations effect

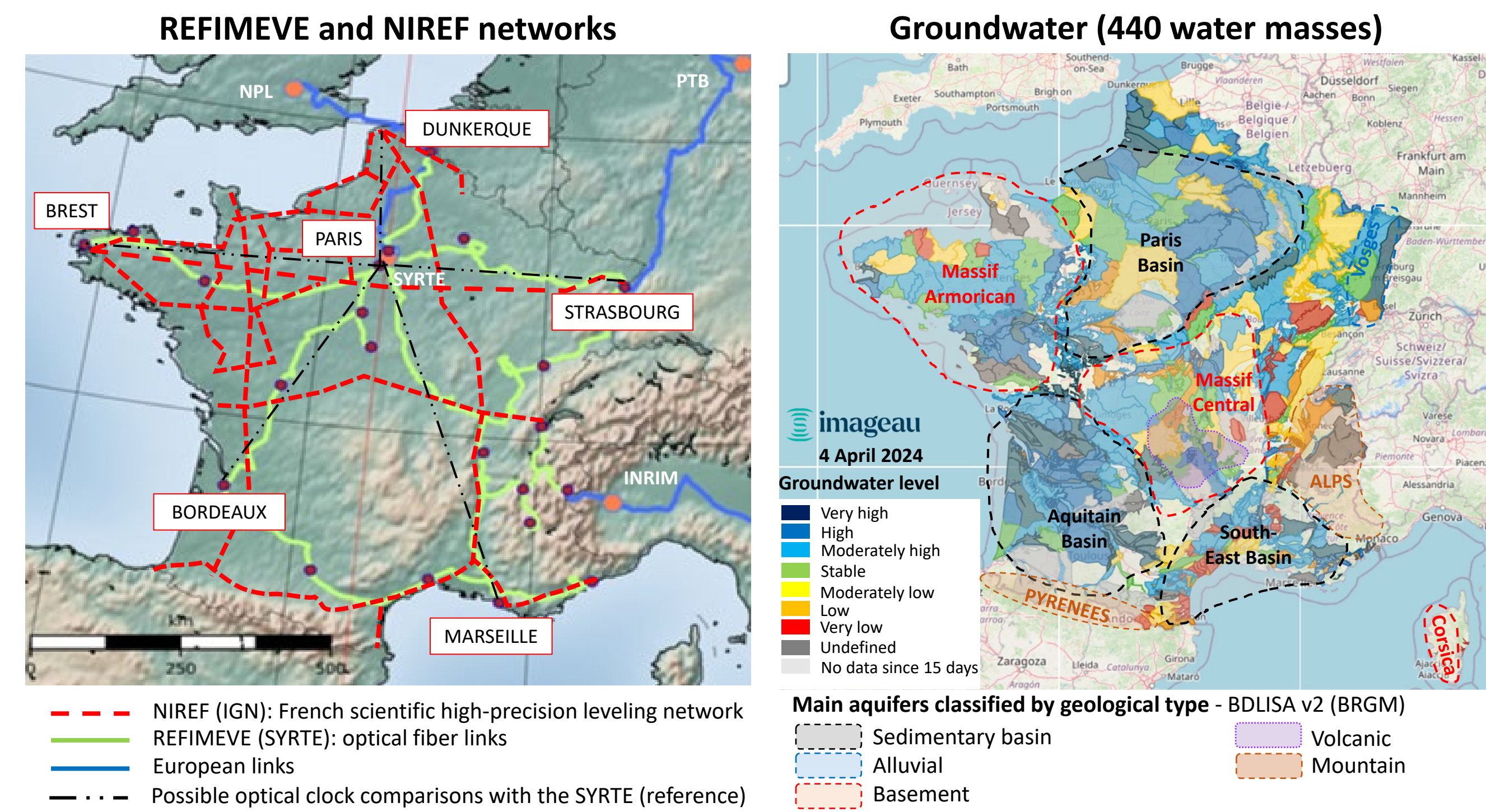
Field clock senses $\Delta \rho < 0 + \text{subsidence}$ Field clock senses $\Delta \rho > 0 + \text{uplift}$

Application to the aquifers



- Vertical deformations of the Earth's surface due to subsidence/uplift
- Temporal variations of gravity field and geopotential due to mass transfer
- Clock comparisons can help track changes in water mass and associated ground movements

Groundwater and coverage of fiber and leveling networks



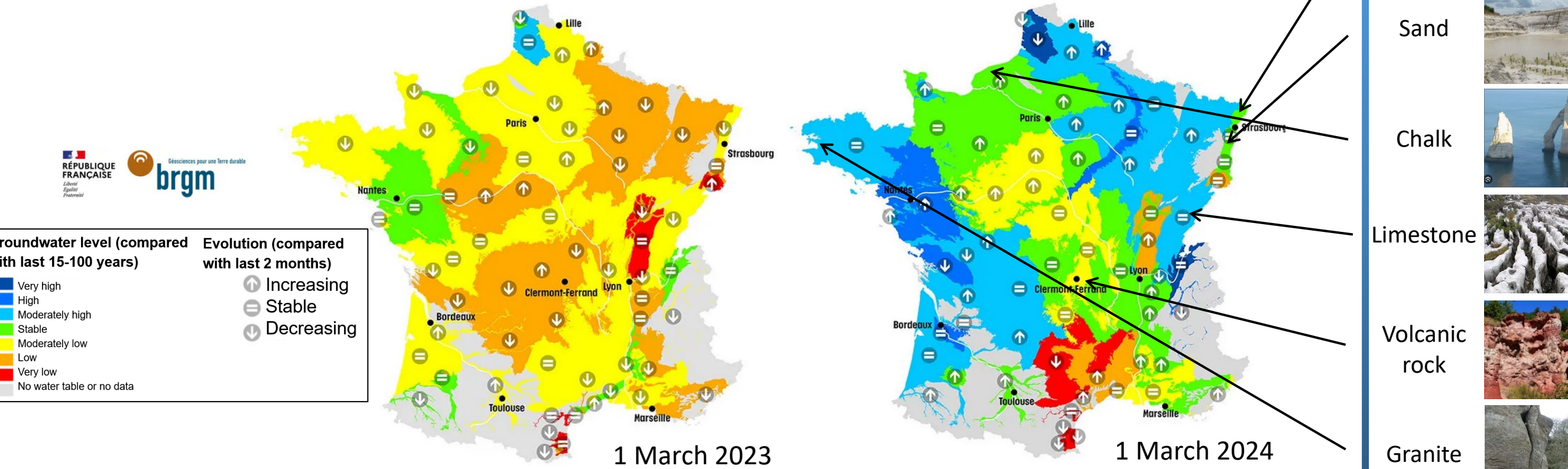
- Both networks cross groundwater tables
- Several segments of NIREF overlap with REFIMEVE
- Variations in aquifer hydraulic head can induce vertical ground motions at local and regional scales

- Deformation of a leveling network
- Can clocks contribute to improving the vertical reference?

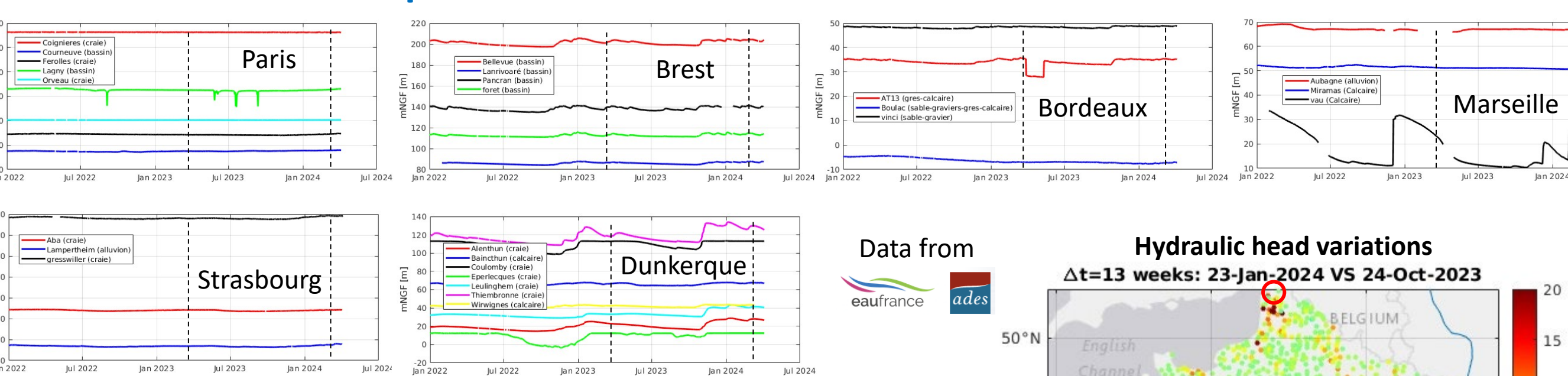
Groundwater level variations

Managed by the BRGM, the French geological survey

- 6500 aquifers including 200 regional-scale aquifers (1 000 to 100 000 km²)
- Manage a national piezometric network with 1 600 boreholes
- Diverse rock types leading to different permeabilities
- Some regions are more affected by climate change, rainfall, pumping and natural groundwater recharge



Data from several piezometers around REFIMEVE



- Average hydraulic head variations around 1-5 meters
- Some piezometers have recorded a recharge >10 m in few weeks after the drought period in 2023 and the heavy rains of recent months
- Over the past 10 years, variations can reach 10-15 m in few months, but fluctuations can reach 30 m
- Some aquifers are no longer able to fully recharge, loss of 1 m/yr

→ What is the gravitational response and associated vertical ground deformation at regional scales?

Simulations

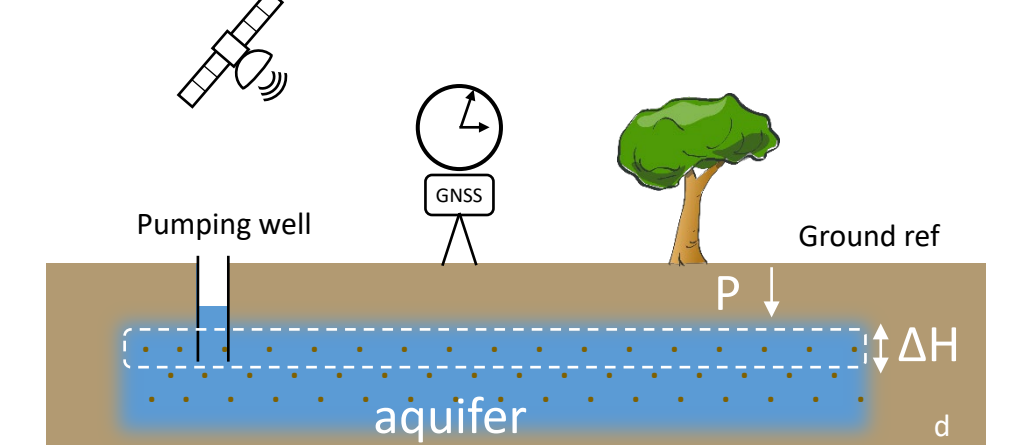
Gravitational signal and vertical displacement → Lion et al., in prep

- Clock comparisons integrate the effects at both the reference and compared stations
- The signal must be corrected for classical gravitational effects in order to characterize the displacement u_{az} and the gravitational potential changes ΔV due to the aquifer(s)
- We assume no hydrological variation near the reference clock

Geopotential variations: $\Delta W = \Delta \Phi + \Delta V_{SET} + \Delta V_{OTL} + \Delta V_{PM} + \Delta V_{aqui} + (\dots)$

- Φ and $V_{PM} \rightarrow$ IERS 2010 conventions; $V_{OTL} \rightarrow$ FES2014b
- $V_{SET} = V_t + \delta V_t - g \cdot u_{tz} \rightarrow V_t$: direct tidal effect; δV_t : Earth deformation; u_{tz} : surface change or $V_{SET}^{(n)} = (1 + k_p - h_p) V_t^{(n)} \rightarrow$ Harmonic tables of tide-generating potential (HW95) + elastic response of the Earth tides via Love number theory
- $V_{aqui} = V_a - g \cdot u_{az}$

- V_a : gravitational potential of an aquifer
- Right rectangular prism at depth P
- Dimension: $120 \times 60 \times \Delta H$ [km³]
- See for e.g. Mader (1951)



u_{az} : vertical displacement of compacting reservoir → See for e.g. Barbosa et al. (2022)

Peak-to-peak value - From 03/2023 to 03/2024

ΔV effects [m ² /s ²]	Centrifugal Φ	Solid Earth Tide V_{SET} (u_{tz})	Ocean Tide Loading V_{OTL}	Polar motion V_{PM}	Max effect				
					P (m)	$\Delta H=1\text{m}$ V_{aqui} (u_{az})	$\Delta H=5\text{m}$ V_{aqui} (u_{az})	$\Delta H=10\text{m}$ V_{aqui} (u_{az})	$\Delta H=20\text{m}$ V_{aqui} (u_{az})
Paris (ref)	48201.56	5.11 (46)	0.03	0.17	-	-	-	-	
Bordeaux-Paris	7182.85	0.67 (6)	0.04	<0.01	100	<0.01 (0)	0.12 (1)	0.24 (2)	0.58 (5)
Brest-Paris	3.34	0.90 (8)	0.12	0.02	20	0.01 (0)	0.03 (0)	0.07 (0)	0.13 (0)
Dunkerque-Paris	-5022.91	0.28 (3)	0.03	<0.01	10	<0.01 (0)	0.03 (0)	0.06 (0)	0.18 (1)
Marseille-Paris	9756.18	0.87 (8)	0	<0.01	10	<0.01 (0)	0.03 (0)	0.06 (0)	0.18 (1)
Strasbourg-Paris	1740.82	0.71 (6)	0	0.02	30	<0.01 (0)	0.03 (0)	0.10 (1)	0.28 (2)

Simulations use coarse rheological parameters for each geological area: Young's modulus E (20 GPa for Brest, 500 MPa otherwise), Poisson's coeff $\nu=0.25$, uniaxial compaction $C_m=0.8/E$, mean porosity with a density of 2.6 (granit, sandstone) for Brest and 1.6 (clay, marne) otherwise

→ With centimeter variations, these preliminary results show that clock measurements could be sensitive to hydraulic changes in aquifers

Perspectives

- Build a catalog of hydrological basins with their physical and rheological properties
- Make more realistic simulations for each water mass (rectangular prism discretization)
- Extend the study for each REFIMEVE nodes
- Decoupling a geopotential signal from the vertical displacement
- Analysis of the InSAR products (e.g. EGMS) and GRACE solutions at local/regional scales
- Generate interferograms using Flatsim (ForM@Ter service) from Sentinel-1 data
- Characterize the geodetic network with clocks, GNSS, InSAR and GRACE data

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