QUALITY OF THE BARRIER

ADDITIONAL INFORMATION ON THE SITING PROPOSAL

The Opalinus Clay is the core unit of the geological barrier. It is of similar quality in all three regions. Safety analyses show that the Opalinus Clay alone can very effectively confine the radioactive waste for a long time period. The adjacent confining geological units are also very tight and make an additional contribution to the containment of the radionuclides and thereby also to long-term safety. The confining geological units have a more variable composition in the three siting regions than the Opalinus Clay and extend to the next over- and underlying aquifers (groundwater-bearing rock layers).

The distance from the centre of the Opalinus Clay to the nearest aquifer, i.e. the thickness of the low-permeability rocks enveloping the repository, is an indicator of the quality of the geological barrier. This aspect of quality will therefore be discussed in more detail in the first part of this document based on the results from the deep borehole campaign.

The second part takes a closer look at the topic of ancient porewaters introduced in Nagra's report on the siting proposal. The composition of the ground- and porewaters is the result of transport processes in the past and can be used as an indicator of barrier efficiency. The differences between the siting regions in this respect are shown and classified using various figures.

nagra.

DISTANCE TO NEAREST AQUIFER

Based on hydrogeological investigations in the deep boreholes, it is possible to distinguish between low-permeability rocks and aquifers (Figures 1 and 2). The distance from the centre of the Opalinus Clay to the over- and underlying aquifers varies between the three siting regions.

JURA OST

Beneath the Opalinus Clay, the Keuper aquifer is the nearest zone with groundwater flow. This could be observed in all three deep boreholes. The situation above the Opalinus Clay is more complicated: observations from the westernmost borehole, Bözberg-2-1, indicate groundwater flow in the Hauptrogenstein, but this aquifer could not be detected in the Bözberg-1-1 borehole. No hydrogeological investigations of these geological units were carried out in the previously drilled borehole in Riniken. The different hydrogeological observations in Bözberg-1-1 and Bözberg-2-2 can be explained with the presence of different rock types: low-permeability rocks rich in clay minerals and/or marl can frequently be found in the eastern part of the siting region, while the higher-permeability, limestone-rich Hauptrogenstein can be observed in the western part. The transition between limestone rocks and rocks rich in clay minerals is complex and geographically difficult to delimit in detail.

NÖRDLICH LÄGERN

In Nördlich Lägern, the Muschelkalk aquifer forms the regional aquifer below the Opalinus Clay. Only the Stadel-2-1 and Bachs-1-1 boreholes indicate the existence of a transmissive Keuper aquifer. Here, transmissive sections are linked to sandy deposits that can only be found locally. As a result, the transport distance to the aquifer below the Opalinus Clay is longer in these sections than in the other siting regions. Above the Opalinus Clay host rock, the Malm aquifer forms the regional aquifer, whereby the observed permeable zones all lie in the upper part of the Malm limestones. The Herrenwis Unit (coral reef) is not classified as an aquifer based on findings from the Bülach-1-1 and Stadel-3-1 boreholes.

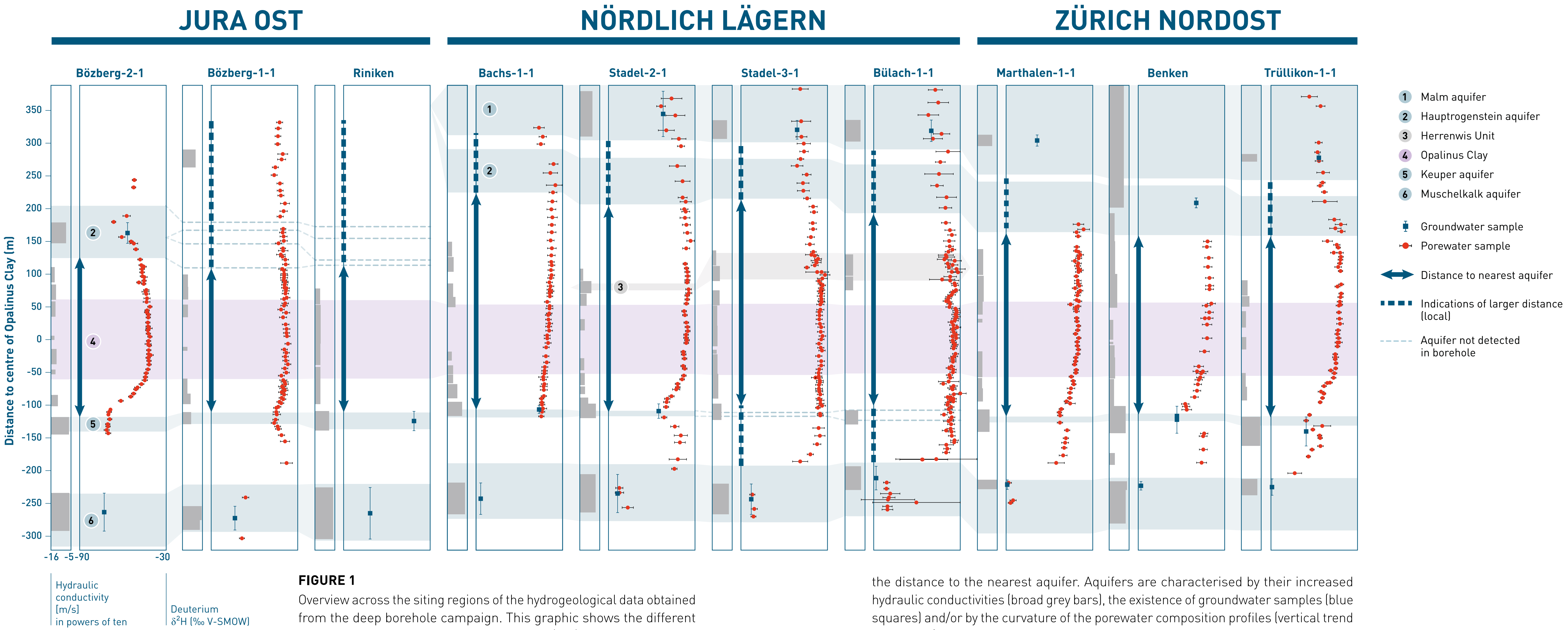


FIGURE 1

Overview across the siting regions of the hydrogeological data obtained from the deep borehole campaign. This graphic shows the different units, the hydraulic conductivities, deuterium (δ^2H) in the porewater and the distance to the nearest aquifer. Aquifers are characterised by their increased hydraulic conductivities (broad grey bars), the existence of groundwater samples (blue squares) and/or by the curvature of the porewater composition profiles (vertical trend of red dots).

ZÜRICH NORDOST

In Zürich Nordost, all boreholes indicate the presence of a Keuper aquifer below the Opalinus Clay. This also applies to the Rheinau borehole, which is not included in this graphic. The local Keuper aquifer appears to be active throughout the siting region. The nearest aquifer above the Opalinus Clay is formed by the thick Malm limestones (Malm aquifer in Figure 1), which could be confirmed in observations from the Benken, Trüllikon-1-1 and Marthalen-1-1 boreholes.

COMPARISON OF THE SITING REGIONS

Upwards, the distance to the nearest aquifer in the Jura Ost siting region is, at least to the west, significantly smaller than in the other regions, which can be attributed to the Hauptrogenstein. In comparison, in Nördlich Lägern, the distance is largest.

Downwards, all boreholes drilled in the Jura Ost and Zürich Nordost siting regions indicate the presence of a Keuper aquifer. In Nördlich Lägern, this aquifer was only observed locally and is linked to permeable sandy layers. In comparison with Jura Ost and Zürich Nordost, the distance in Nördlich Lägern to the nearest water-bearing layer below the Opalinus Clay is locally greater.

PROFILES OF NATURAL TRACERS IN THE POREWATER

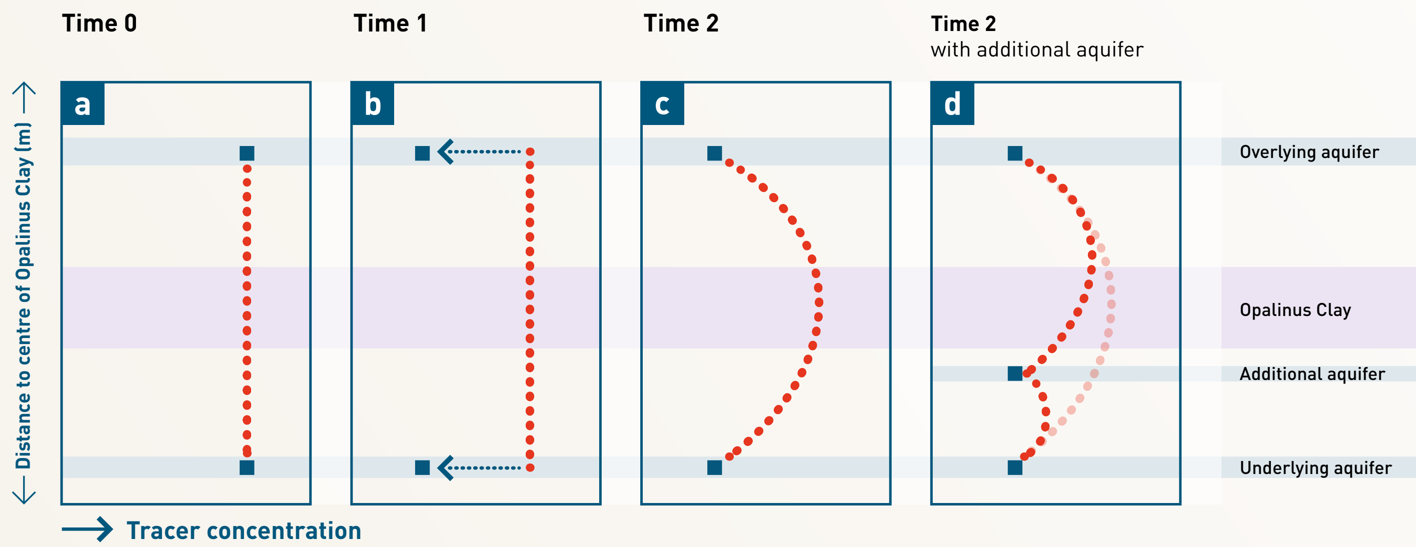
As opposed to the groundwater in the aquifers, the porewater enclosed in low-permeability rocks cannot be pumped from the boreholes, but has to be extracted from the drill cores in a sophisticated experimental procedure.

Together with the composition of the deep groundwaters (dark blue squares in Figures 1 and 2), the trend of the porewater composition along the borehole (profile of the natural tracers; red dots in Figures 1 and 2) delivers important information on past transport processes (last 100,000-1,000,000 years). When a deep aquifer is activated, near-surface groundwater with a different composition can flow deep below ground. As a result, it is possible, for example, for originally deep marine groundwater to be replaced by meteoric water (Figure 2b).

Due to slow exchange processes between ground- and porewaters, in particular diffusion, the composition of the porewater approaches that of the groundwater over a very long time period, thus increasing the proportion of meteoric water in the porewaters. The slow exchange process between ground- and porewaters produces the typical rounded vertical profiles of the natural tracers (see Figure 2c).

Using numerical simulations, it is possible to show that the typical time period for the formation of such rounded profiles is in the range of several hundreds of thousands of years. The profiles thus reflect an effective barrier function of the clay-rich rocks over long time periods. Prominent curvature in the vertical profiles of the natural tracers indicates the presence of aquifers (Figure 2d).

CONCENTRATION OF NATURAL TRACERS



INITIAL STATE
Non-active aquifers (stagnating situation)

NEW BOUNDARY CONDITIONS
Activation of aquifers (e.g. infiltration of meteoric groundwater)

CONDITION AFTER LONG TIME PERIOD
Exchange processes between ground- and porewaters create a rounded profile of the tracer concentration in the porewater.

CONDITION AFTER LONG TIME PERIOD WITH ADDITIONAL AQUIFER
The double curve depicts an additional zone with groundwater flow.

FIGURE 2
Schematic representation of the temporal evolution of the composition of the ground- and porewaters. The x-axis represents the concentration of a natural tracer, and the y-axis shows the thickness of the rock column typical for Northern Switzerland, including the Opalinus Clay, adjacent low-permeability rocks and the nearest aquifers.

COMPOSITION OF GROUND- AND POREWATERS

The isotopic composition of the water molecule (H_2O) from different samples can be visualised by means of a diagram showing the ratios of oxygen ($\delta^{18}O$) and hydrogen isotopes (δ^2H) (Figure 3). In this type of representation, the compositions of rainwater and near-surface, young groundwater are on the so-called meteoric water line. These waters are also called meteoric water. The specific composition of a sample depends on the climate. Precipitation from past cold periods, for example, has a significantly different water isotope composition compared to present-day meteoric water. The former would plot at the very bottom left of the chart and the latter higher up on the meteoric water line. Fossil seawater components contained in the porewater plot not on the meteoric water line but to its right. Values that are not on the meteoric water line can alternatively be caused by very slow exchange processes between the rock and the water. Porewater compositions near the meteoric water line indicate a more intensive exchange with younger water formed by precipitation (meteoric water).

The composition of the porewater in the Opalinus Clay is the results of the geological evolution of Northern Switzerland and developed due to the exchange with water from adjacent aquifers. The properties of the low-permeability layers and the distance and flow dynamics in the aquifers also play a role in this process.

Differences between the three siting regions can be observed in the composition of the porewater in the Opalinus Clay (Figure 3). These can be explained as the result of different stages of a mixture between fossil (particularly old, to the right of the meteoric water line) and younger meteoric water. In Nördlich Lägern, isotope compositions of the porewater of the Opalinus Clay can be observed to be furthest to the right of the meteoric water line. In contrast, they are closer to the meteoric water line in Zürich Nordost and particularly in Jura Ost where they are more strongly overprinted through their interaction with meteoric water.

POREWATER OPALINUS CLAY

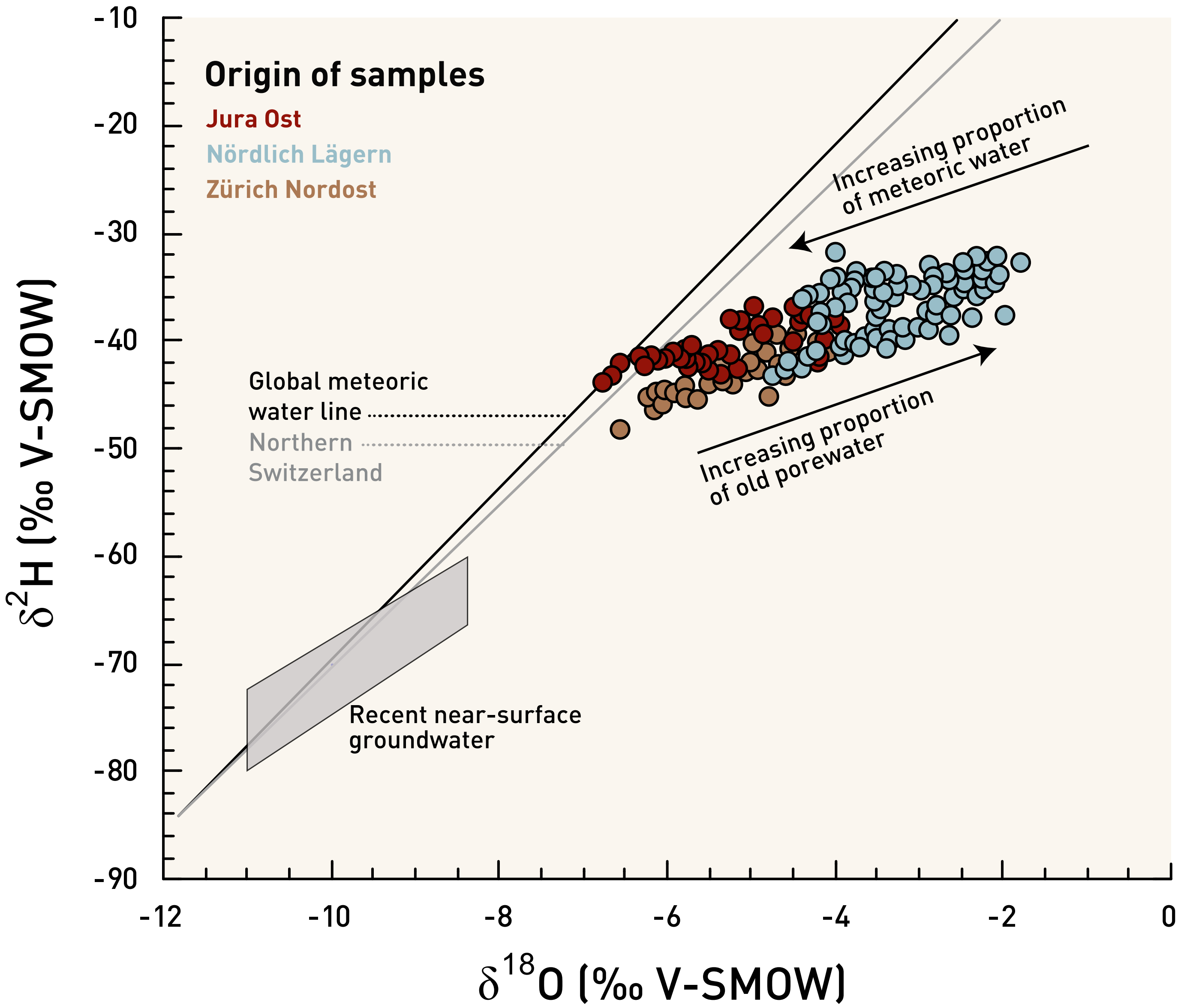


FIGURE 3
Comparison of the isotope composition of the water molecule in the Opalinus Clay porewater in the three siting regions.

The porewater composition in the Opalinus Clay is influenced by very slow diffusive exchange with the water in the nearest aquifers. To understand past transport processes and how they differ between the siting regions, it is therefore important to also consider the composition of the groundwater (Figure 4).

JURA OST

Here, the composition of the porewater in the Opalinus Clay is related to the groundwater compositions at or near the meteoric water line (Figure 4). Overall, the investigations of the ground- and porewaters show that their interaction with near-surface, meteoric water strongly impacts the system.

NÖRDLICH LÄGERN

In this region, the composition of the Opalinus Clay porewater is linked to the uniform isotope compositions of the Malm groundwaters enriched in δ^2H and δ^{18}O (to the right of the meteoric water lines; Figure 4); these types of compositions are indications of particularly long residence times of the ground- and porewaters. Samples from the Keuper aquifer could only be extracted from two boreholes (cf. Figure 1). The composition of the isotopes contained in these samples plots to the right of the meteoric water line. Overall, the data from the ground- and porewaters from Nördlich Lägern show that some particularly old components of these waters have been preserved, and comparatively little exchange with near-surface meteoric water has taken place.

ZÜRICH NORDOST

Here, the porewaters in the Opalinus Clay in the different boreholes show almost identical isotope compositions, which are influenced mainly by the interaction with the groundwater in the Keuper aquifer (Figure 4). The Malm groundwaters show significantly different compositions between the boreholes, which can be explained by different percentages of younger meteoric water. Trüllikon-1 shows a similar isotope composition to the boreholes in Nördlich Lägern. On the other hand, the Malm groundwater in Marthalen-1 has a similar composition to recent groundwaters. Overall, the investigations in Zürich Nordost highlight the significance of the Keuper aquifer as an aquifer beneath the Opalinus Clay and a locally higher flow dynamic of the Malm aquifer compared to Nördlich Lägern.

COMPARISON OF THE SITING REGIONS

The isotope distribution in the water molecules of the Opalinus Clay porewater differs between the siting regions. In Nördlich Lägern, the composition of ground- and porewaters lies furthest from the meteoric water lines; here, particularly old porewater components have been preserved. The isolation performance of the overall geological system (disposal level to surface) in the past was most effective here.

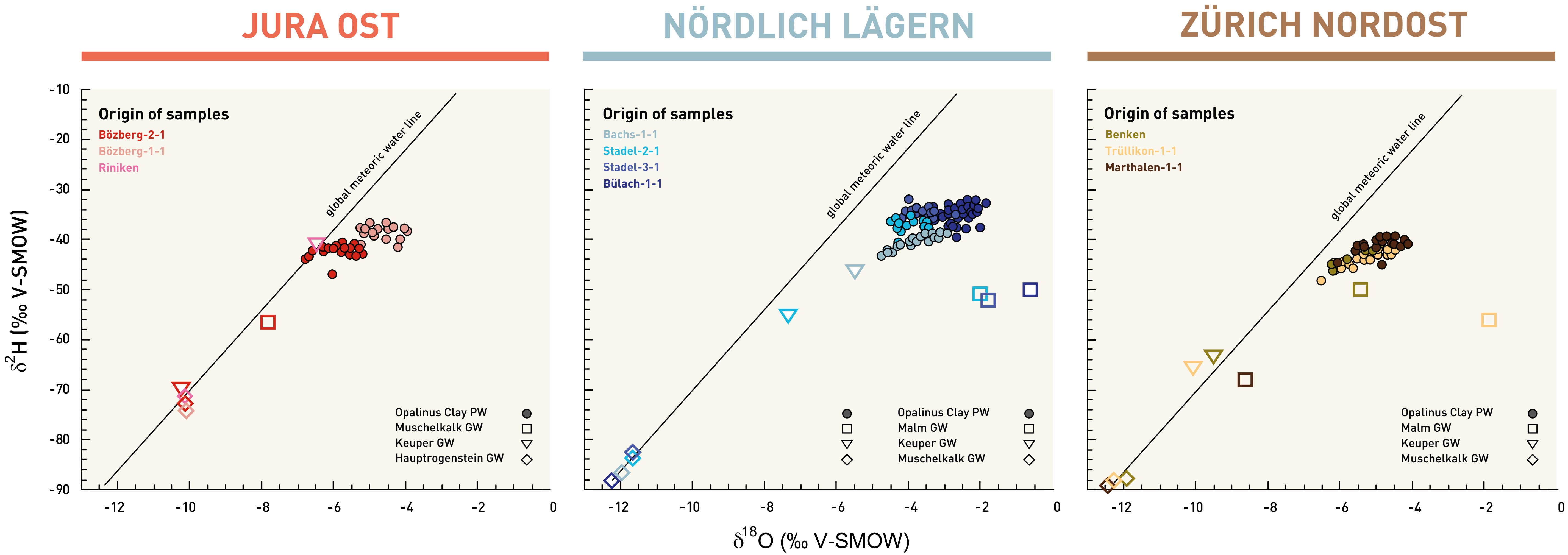


FIGURE 4
Porewater (PW) composition of the Opalinus Clay in the deep boreholes in comparison with groundwater (GW) samples for all three siting regions.

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