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### Association between discharge areas of groundwater and volcanic $CO_2$

by K. Udo Weyer[1) 3)], Franz May[2)] and James Ellis[1)]

1) WDA Consultants Inc. Calgary, Canada: weyer@wda-consultants.com
2) BGR, Federal Institute for Geosciences and Natural Resources, Hannover, Germany
3) WKC Consultants, Krefeld, Germany

### Introduction

Geologic storage of $CO_2$ is often seen as a static system whereby the $CO_2$ is kept in storage by the "impermeable" caprock. Only vertical buoyancy forces would act upon the stored $CO_2$ in reservoirs. For saline aquifers it is claimed that the addition of $CO_2$ increases the density of the saline water and this would cause the $CO_2$-enriched saline water to move downward to the bottom of sedimentary basins where it would be safely stored for millions of years. All these assumptions are incorrect as can be shown by applying the physics of Hubbert's (1940) Force Potential to CCS (Weyer, 2010). Weyer (2010) also showed that flowing groundwater would dissolve stored $CO_2$ and carry it along its flow path to regional groundwater discharge areas. There, salty and $CO_2$-containing water would, in minor amounts, discharge from below into the centre of rivers and lakes (compare Fig. 1 and 2) .

**Fig. 1** Natural discharge of $CO_2$ at the Crystal Geyser on the bank of the Green River, Utah, as the end point of a large-scale regional groundwater flow system. (Picture by Weyer, Feb 2010)

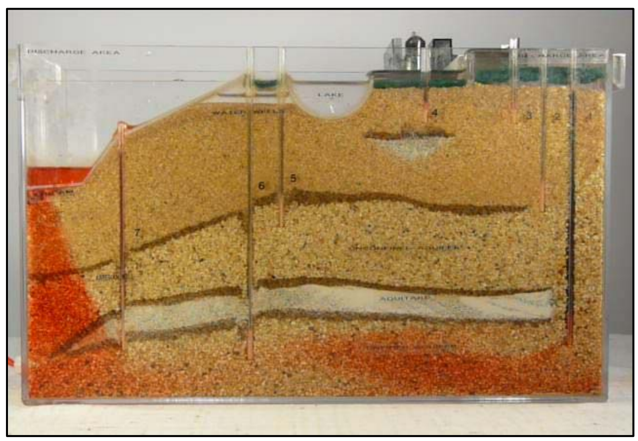

**Fig. 2** Model demonstration of deep groundwater flow with a plume of dissolved $CO_2$ entering a surface water body from underneath.

As groundwater flow systems reach to great depth by penetrating aquitards (caprocks), any successful design of on-shore geological carbon storage must regard the migration effects groundwater flow systems exert on stored $CO_2$. In most cases all of the $CO_2$ will be dissolved by groundwater and migrate to the discharge areas of these flow systems.

Deep groundwater flow will transport the dissolved $CO_2$ towards groundwater discharge areas and thereby into surface waters. A telling example of such a system is the Green River in Utah with its natural discharge points of natural $CO_2$ and the artificial discharge point Crystal Geyser, a flowing abandoned well located at the bank of the Green River (Fig. 1). Fig. 2 shows the manner in which the abandoned flowing well at the Green River intersects the $CO_2$ plume (red colour). Comparing both figures, the upward flow of the $CO_2$-containing groundwater is indicated by the artesian discharge in wells close to the surface water bodies.

Hydrogeological tools have been developed which allow the determination of the flow paths of deep groundwater flow systems and the approximate time scale to reach their groundwater discharge areas. These time spans may reach orders of magnitude of tens of thousands of years and the amount of $CO_2$-rich groundwater entering the surface water will be miniscule in comparison to the volume of surface water flow. Therefore no major environmental impacts are anticipated (Weyer, 2010). Residence times in the thousands of years or more would in all likelihood suffice in mitigating any atmospheric effect caused by the discharge of $CO_2$.

**Field Investigation: West Eifel, Germany**

The above concepts have so far not created much resonance in the scientific and practical world of geologic $CO_2$ storage. Therefore the investigation of groundwater dynamics at areas with natural discharge of volcanic $CO_2$ provides a test for the effect groundwater flow systems will exert on the geologic storage of $CO_2$. The Eifel area in Germany presents such a natural laboratory. It contains several hundred known Quaternary volcanoes (Fig. 3), a number of which provide pathways for $CO_2$. The major $CO_2$ groundwater discharge points are well-known as they have been used for centuries for the production of carbonated mineral waters and for spas. May (2002a, 2002b) listed wells and natural discharge points containing $CO_2$ in the West-Eifel. The distribution of $CO_2$ discharge points indicates that $CO_2$ ascends from fragmented sedimentary rocks of the Variscan basement through volcanic systems and through lineaments as indicated by May (2005).  Figure 4 shows a cold geyser in a groundwater discharge area within the village of Wallenborn.

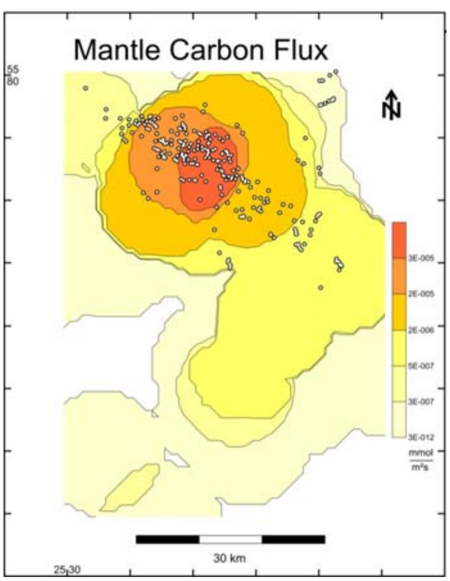


**Fig. 3** Regional average of mantle-C flux densities (mmol/m$^2$/s) in the West- and South-Eifel. Circles mark the eruption centers of the quarternary volcanoes of the West-Eifel (from May, 2002b).

**Fig. 4** $CO_2$ geyser Wallenborn-Brubbel. For location see Figure 6. The geyser erupts every 35 minutes. It was created in 1933 when a borehole for mineral water production had been advanced to 30 m depth.

Groundwater recharge and discharge areas are evident from high resolution digital topographical maps of the area (data provided by Landesamt für Vermessung und Geobasisinformation Rheinland-Pfalz and GEObasis.nrw). Topography is the first-order determinant controlling the elevation of the groundwater table in the West-Eifel. Groundwater discharges into the network of rivers, creeks and lakes. Büchel and Mertes (1982) mapped the locations of volcanic eruption centers in the West-Eifel. After combining the above information in a series of small scale DEMs created with 'SURFER' it became obvious that all known natural CO2 discharge points are directly related to groundwater discharge areas while the occurrence of volcanic eruption centers are concentrated in the recharge areas for regional groundwater flow (Figures 5, 6, and 7).

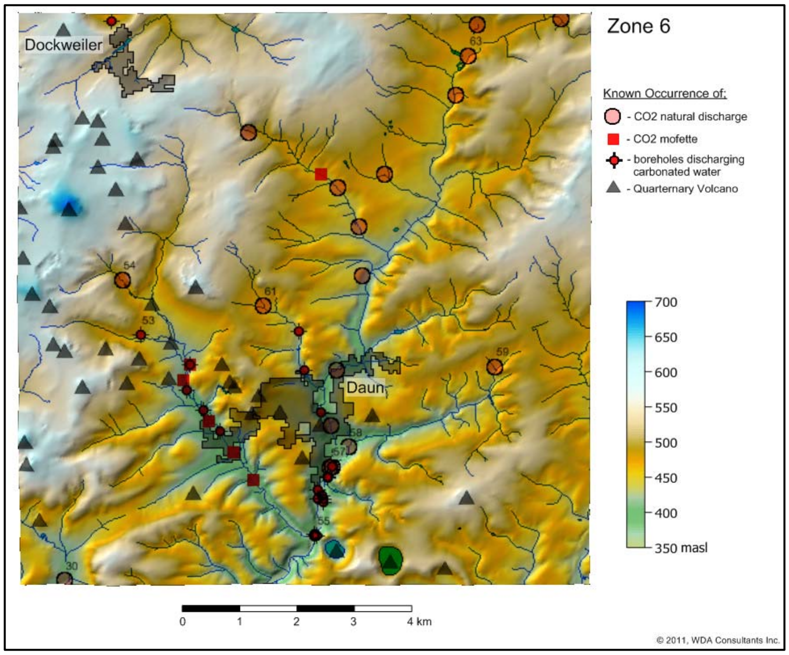


**Fig. 5** Occurrences of $CO_2$ dissolved in groundwater and as mofettes in the Daun area, West-Eifel. $CO_2$ occurrences are directly associated with groundwater discharge areas (rivers and creeks). Boreholes shown serve for the production of carbonated waters.

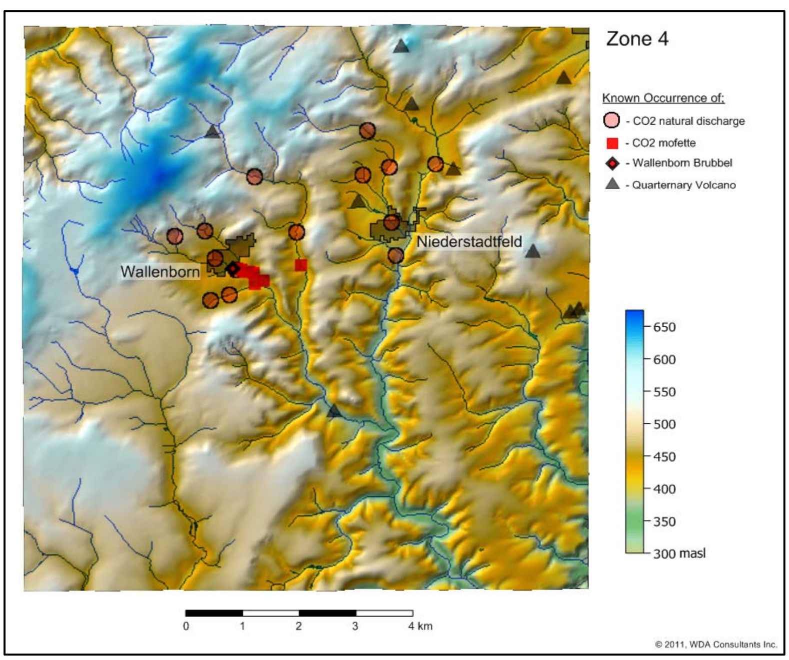


**Fig. 6** Occurrence of $CO_2$ dissolved in groundwater and as mofettes in the Wallenborn area, West-Eifel. $CO_2$ occurrences are directly associated with groundwater discharge areas (rivers and creeks). The cold geyser 'Brubbel' is located within the village of Wallenborn.

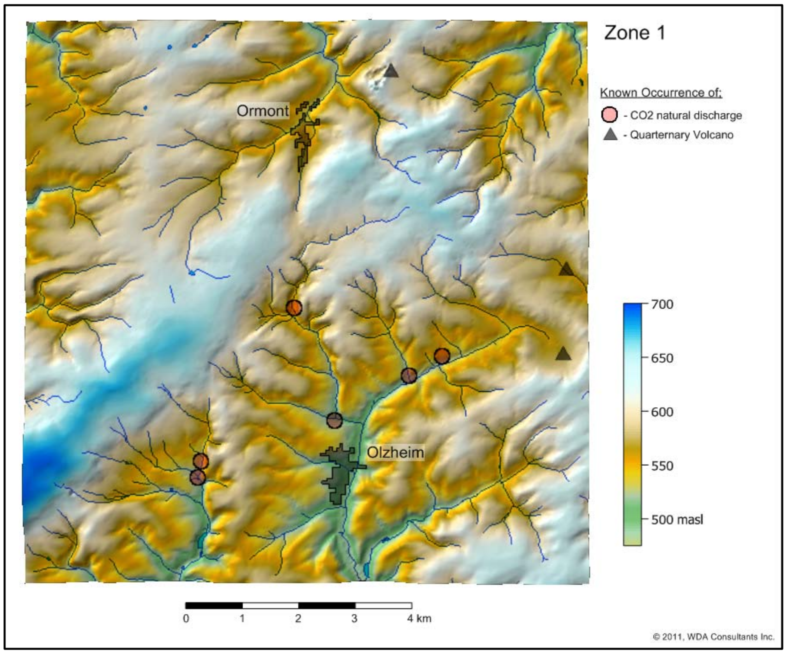


**Fig. 7** Occurrences of $CO_2$ dissolved in groundwater in the Olzheim area at the foot of the Schneifel, West-Eifel. $CO_2$ occurrences are directly associated with groundwater discharge areas (rivers and creeks).

In the valleys surrounding the town of Daun (Fig. 5), many boreholes are producing mineral water. The area is well populated without any obvious effects on the health of the inhabitants. It is actually a tourist area.

Figures 5 and 6 also show the occurrence of mofettes where $CO_2$ gas is pearling out of the groundwater discharging into the creeks. Due to reduction of pressure while the groundwater flows upwards, there is in fact so much gaseous $CO_2$ escaping that, in the Village of Wallenborn, a cold geyser erupts regularly close to the local creek (Fig. 4).

Figure 7 depicts discharge from an apparent fault zone as indicated by the linear distribution of $CO_2$ discharge points in two adjacent valleys. No $CO_2$ sources have been observed in the recharge area between the two valleys. This emphasizes the fact that it is the groundwater flow which determines the discharge points of $CO_2$ migrating up from greater depth.

**Conclusions**

Discharge areas of groundwater flow systems determine the natural discharge points for $CO_2$ of mantle origin and they will also dominate the long-term migration of sequestered $CO_2$. Thus, successful storage of $CO_2$ needs to be based on a Geofluids System Analysis. Hydrogeological methodologies for the study of regional gravitational groundwater flow systems need to be applied to any successful geological storage of $CO_2$.

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