Tademait Plateau: A regional groundwater recharge area in the centre of the Algerian Sahara

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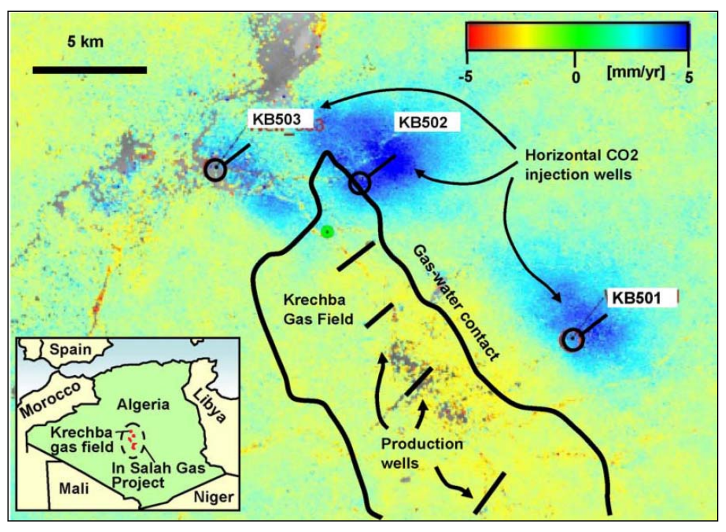
Introduction

The injection of CO_2 at 'In Salah' (Krechba gas field) in the Algerian Sahara tests the behaviour of the sequestered CO_2 in the subsurface. Figures 1 and 2 depict the occurrence of the Krechba gas reservoir in approximately 1850 m depth in 20 m of Carboniferous sandstone. It is overlain by 900 m of Carboniferous mudstone, 700 m of Lower Cretaceous sandstone, an aquifer, and 200 m of Middle and Upper Cretaceous mudstone. In a newly drilled observation well the water level from the aquifer rose to about the middle of the overlying Cretaceous mudstone. When drilling through the Carboniferous mudstone, loss of circulation was frequently encountered in the upper 400 m and lower 200 m of the mudstone, a caprock in oil field terminology, an aquitard in hydrogeological terminology. It is under debate whether the circulation losses were caused by pre-existing fractures or by hydraulic fracturing (Iding & Ringrose, 2009).



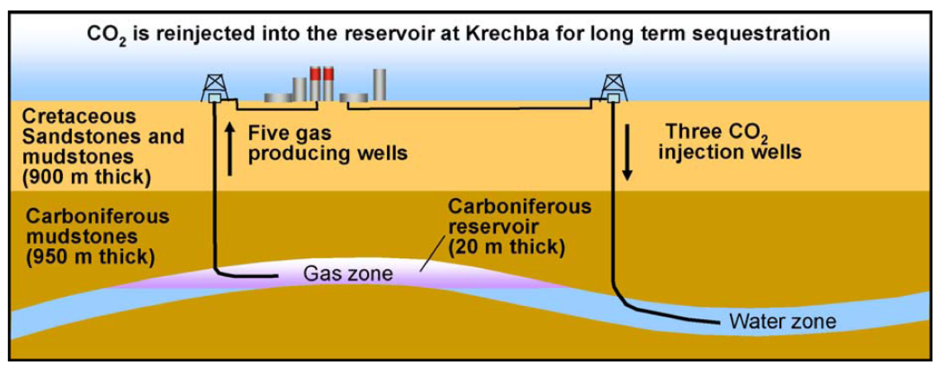


Fig. 2 General geology and technical installations at the Krechba gas reservoir (from Rutqvist et al., 2010, Fig. 1)

Fig. 1 InSAR data of average distance change (close to vertical displacement) evaluated by TRE from August 2004 to March 2007 (from Rutqvist et al., 2010, Fig. 2).

The Cretaceous aquifers of the Tademait Plateau belong to the 'Aquifère du Continental Intercalaire' system (Castany, 1982). Traditionally much of the groundwater flow in the Sahara Basin was seen as originating in the Atlas Mountains and shown to underflow the Tademait Plateau partially from northeast to south and partially from northeast to southwest (Ben Dhia, 1991, his Fig.4 and 5). The guiding concept was the conceptual model that groundwater flow would be limited to aquifers themselves and, in this case, to an aquifer system with an outcrop and thereby recharge area in the Atlas Mountains. In Groundwater Flow Systems theory aquitards at the surface (Figure 3) were shown to be natural recharge areas for deeper aquifers by Freeze & Witherspoon (1967). Tóth (1962) had introduced the concept of Groundwater Flow Systems with recharge and discharge areas whereby the penetration depth can exceed 5 km (Tóth, 2009). In a recharge area the flux of groundwater crosses the groundwater table into the saturated domain; in a discharge area the flux of groundwater is directed from the groundwater body into surface waters or to the surface for evaporation.

Behaviour of sequestered CO_2 in the Krechba field

Unexpectedly the geo-mechanical behaviour and flow direction of the injected CO_2 did not follow predictions. Firstly, rises of surface elevations of several centimeters have so far been measured by satellites (Fig. 1 and 2). Secondly, the areal extent of these uprising areas showed that in about 2000 m depth the CO_2 migrates down dip and, in a northwestern direction away from the pressure sink of the gas production area which is located up dip of the CO_2 injection sites (Fig. 1). Both, gas reservoir and CO_2 injection site are located within the same Carboniferous sandstone of approximately 20 m thickness (Fig. 2).

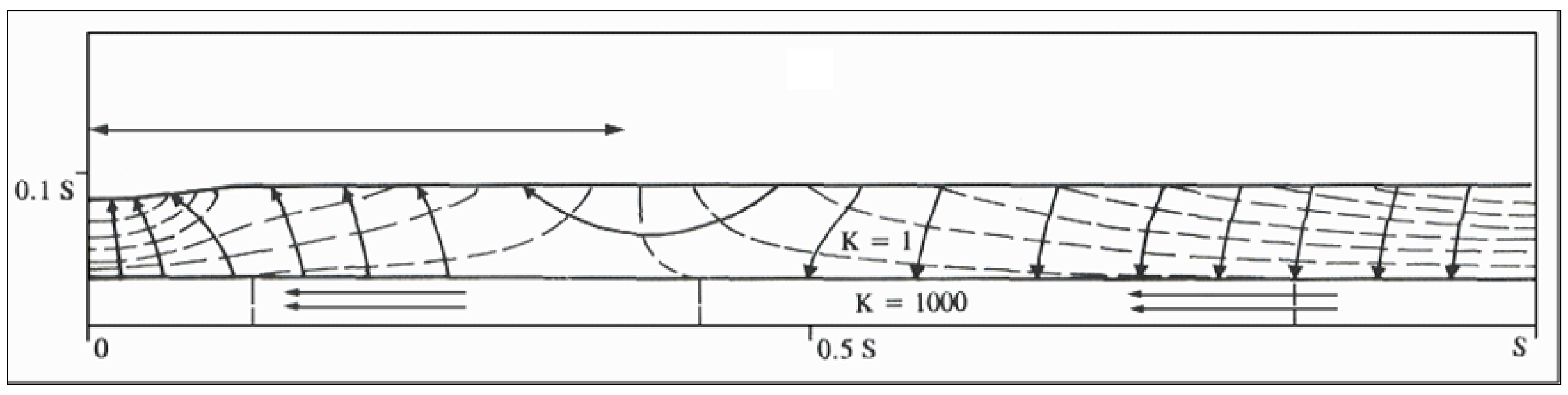


Fig. 3. Groundwater flow through an aquitard to the underlying aquifer and back to the discharge area indicated by the double-headed horizontal arrow. (after Freeze & Witherspoon, 1967). The permeability contrast is 1000.

The encountered flow direction cannot be explained by buoyant flow behaviour as had been expected from the supercritical CO_2 fluid with a density of about 0.7 g/cm^3 in a salty host fluid of a density probably exceeding 1.1 g/cm^3. The hydrodynamic behaviour of the CO_2 can be explained, however, by applying Hubbert's (1940, 1953) force potential and groundwater flow systems theory (Tóth, 1962; Freeze & Witherspoon, 1967).

Regional Groundwater Flow in the Tademait Plateau

The Tademait Plateau is a distinctive mountain system in the centre of the Algerian Sahara. It is wedged between the Atlas Mountains to the northwest and the Tefedest Mountains to the southeast (Figure 4). Elevation differences between the main part of the Tademait Plateau and the surrounding lowlands to the SW reach up to 550 metres, with the length of the flow systems exceeding 200 km.

The southwestern edge of the Plateau is highlighted by the occurrence of 81 oases (black dots in Figure 4). According to surface topography and thereby the approximate topography of the groundwater table, 53 of these oases are located on the slopes of the Tademait Plateau with an additional 26 arranged in the down slope area of the Atlas Mountain system. Oases occur in groundwater discharge areas; hence a rim of discharge areas occurs to the west, southwest, and east of the Tademait Plateau. The geometry of these occurrences and hydrodynamic reasons (Weyer, 2010) identify both recharge and discharge areas in this area. The Tademait Plateau is an active and efficient recharge area for regional groundwater flow systems discharging at the oases and in the deeper low lands to the west, southwest, and east of the plateau. At the Krechba site the Cretaceous aquifer system contains fresh water while the Carboniferous reservoir sandstone contains salt water with a TDS of more than 100 g/l (A.S. Mathieson, oral communication, October 2011).

All oases along the southern rim of the Tademait Plateau appear to be located on lower Cretaceous layers, some of them possibly on Jurassic and Triassic layers (Ben Dhia, 1991, his Fig. 2 and 4A). At the Krechba site the Cretaceous layers carry fresh water. The five 'In Salah' oases, in the past, probably used to be fed by fresh, good water from foggaras (qanats) as the name 'good well' implies in Arabic. Since the installation of boreholes for water supply the water is known for 'its rather unpleasant, salty taste' (Wikipedia contributors, 2011). It is therefore probable that these boreholes draw saline water from Carboniferous layers and possibly Triassic salt layers existing in the general area. This would imply that the regional groundwater flow systems also penetrate the Carboniferous layers as they should due to hydraulic reasons. More detailed investigations about flow of recharged groundwater into the Carboniferous layers and the reservoir are under debate.

In any case, the subsurface hydraulic force fields are determined by the groundwater table in fresh water systems and the migration of all fluids is governed by these fresh water force fields and the pressure potential force of the fluid under consideration; hydrous fluids usually pass freely through caprocks (Hubbert, 1953). In all likelihood the migration behaviour of the sequestered CO_2 is caused by fresh water force fields which also exist within brines, regardless of the presence of fresh water. The northwesterly flow direction of the injected CO_2 coincides with the general flow direction of fresh groundwater recharged in the Tademait Plateau and does not coincide with the general southeasterly flow directions shown by Ben Dhia (1991, his Fig. 4A) who assumed groundwater recharge in the Atlas Mountains.

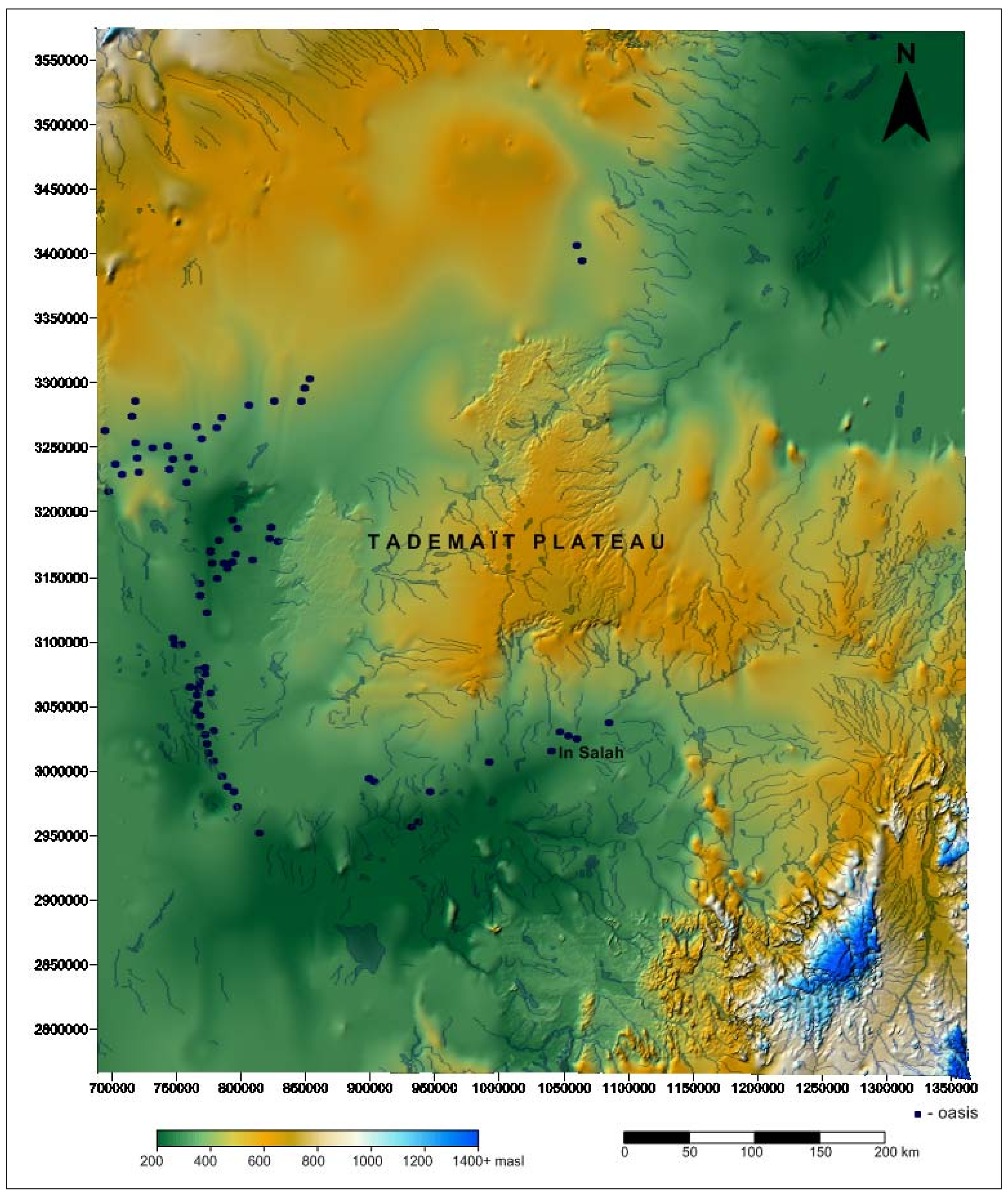


Fig. 4 Topography of the Tademait Plateau (centre) and parts of the Atlas Mountains to the northwest and the Tefedest Mountains to the southeast. A belt of 53 oases are located on the slope of the Tademait Plateau; 26 oases are located on the slope of the Atlas Mountain system. This DEM was based on the USGS' GTOPO30 DEM, transferred into UTM using AutoCAD, and then re-gridded (1 km grid spacing) using SURFER . The locations of the oases were determined from a map with a scale of 1:1,700,000 (World Mapping Project, Algeria).

Infiltration and Groundwater Recharge in Arid Environments

The conceptual model of sustained groundwater recharge in the middle of the Sahara seems to contradict traditional knowledge. For decades the assumption prevailed that, in a desert environment, most of the precipitation would evaporate. In the presence of plants the suction of the root system creates very negative pressures at a depth from 1 to 5 metres (Phillips et al., 2004). This strongly unsaturated zone, permanently maintained by evapotranspiration, prevents, where it exists, substantial recharge to the groundwater system, even if larger amounts of precipitation infiltrate the upper soil layers.

Research at the Yucca Mountain (in the Death Valley area of the Southwestern US) identified soil infiltration rates for soil, plant and exposure conditions through field studies and mathematical modeling. Depending upon the thickness of soil, plant density, and exposure conditions at the sites, infiltration rates reached from 5-10 mm/year up to >250 mm/year (Flint et al. 2001). Higher recharge rates occur where soil over fractured bedrock is less than 0.5 m thick and in topographic depressions such as ephemeral streams (Phillips et al., 2004). Wilson and Guan (2004) confirm that significant recharge can occur where soils are thin or absent over fractured bedrock.

Characteristically most of the area of Tademait Plateau is without continuous plant cover and much of it seems to have thin soil cover over fractured bedrock leading to the conclusion that much of the precipitation may infiltrate the soil and recharge the groundwater body. In addition, at the Krechba site the water table appears to be less than 100 m below surface while it is up to 500 m below surface at the Yucca Mountains implying active infiltration into the soil and recharge to the groundwater body. The actual infiltration rates in the past maintained the water supply of the oases at the rim of the Tademait Plateau system.

Conclusions

The Tademait Plateau has been shown to be an extended and active recharge area for groundwater flow towards a belt of 53 oases to the west, southwest, and south. Recharge occurs through a surface aquitard. The depth penetration of the regional groundwater flow system may be several kilometers but has not yet been determined. In any case, the force field of the fresh groundwater ultimately determines the flow directions of other fluids present in the Carboniferous, including that of the sequestered CO_2. The northern line of 26 oases is supplied with groundwater originating in the Atlas Mountains.

Acknowledgements

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