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Satellite Imaging to Monitor CO_2 Movement at Krechba, Algeria

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Abstract

The Krechba field is one of several gas fields located in the Algerian Sahara desert, and was set in operation in August 2004 as part of a joint venture with BP, Sonatrach and StatoilHydro. The natural gas in the fields contains up to 10% CO_2, which has to be reduced to 0.3% before the gas is sold, resulting in the production of around 1 million tonnes/year CO_2. Rather than vent the CO_2 to the atmosphere (business as usual), it is re-injected into the water leg of the Krechba Carboniferous Sandstone gas producing reservoir (20 m thick) via three horizontal wells at a depth of around 1,900metres. CO_2 injection started in August 2004 and to date nearly 2.5 million tonnes of CO_2 have been injected, amounting to approximately 25% of the gas extracted from the Krechba field over the same period.

A number of key technologies to monitor the injection, and the subsurface movement and storage of CO_2 have been, and will continue to be, deployed to provide long term assurance of sequestration. Time lapse satellite images (using PSInSAR™ Technology) which measure ground deformation to assess the movement of CO_2 in the subsurface have proven to be much more successful than initially thought, despite the depth of injection and the low voidage replacement rate (25%). Satellite images collected since start of injection show clear increases in ground elevation of up to 30mm around the three injectors while subsidence is also apparent in the area of maximum gas production. The images have also confirmed the CO_2 is moving in the direction of preferred fracture orientation at reservoir level. Recent downhole pressure measurements in one of the injectors also indicates that the CO_2 is being contained within the injection horizon. Work is ongoing to integrate the satellite images with geomechanical and seismic data to better understand how these images can be used for monitoring of CO_2 movement in the subsurface.

A key part of the forward monitoring programme will be the acquistion of time-lapse 3D seismic, deployment of tiltmeters and GPS to confirm and calibrate the satellite imagery data, microseismic detectors in shallow boreholes to assess the degree of rock strain and use of shallow wells to monitor the water chemistry in the vadose zone. These will supplement the ongoing tracer, wellhead sampling and satellite imagery data acquistion. This paper shares the latest results of the ongoing CO_2 monitoring project.

Keywords: satellite; CO_2 monitoring; Krechba; In Salah Gas

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1. Introduction

In Salah Gas is a joint venture of BP, Sonatrach and StatoilHydro located in central Algeria (Figure 1), which started in July 2004, producing 900bcf/d gas for sale in Europe. The natural gas contains up to 10% CO_2, which has to be reduced to 0.3% before the gas is sold. Hence, 1 million tonnes/year CO_2 is produced. Rather than vent that CO_2 to the atmosphere (business as usual), this project re-injects it into the Krechba Carboniferous Sandstone reservoir via three long (1500m) horizontal wells at a depth of around 1,900m. CO_2 injection started in August 2004 and over the life of the project, around 14 million tonnes CO_2 is expected to be geologically stored. To date, 2.5 million tonnes of CO_2 has been injected. This project is an industrial-scale demonstration of CO_2 geological storage and is the first industrial-scale project in the world to store CO_2 in the water leg of a gas reservoir.

Figure 1: Location of In Salah Gas Project

The Krechba Field is a large structural anticline with little visible structural disturbance. The CO_2 is injected into a 20m thick, fractured sandstone reservoir with porosities ranging from 11-20% and permeabilities averaging around 10md. The reservoir is capped by around 950m of Carboniferous mudstones that are overlain by approximately 900m of sandstone and mudstones containing the regional potable aquifer (Figure 2). Note that the injection zone is only 20m thick and represents some 1% of the total overburden thickness. Key storage risks were identified as wellbore integrity and direction of CO_2 movement in the subsurface. Vertical leakage into the shallow potable aquifer was not identified as a key risk due to the stratigraphic configuration of the storage site.

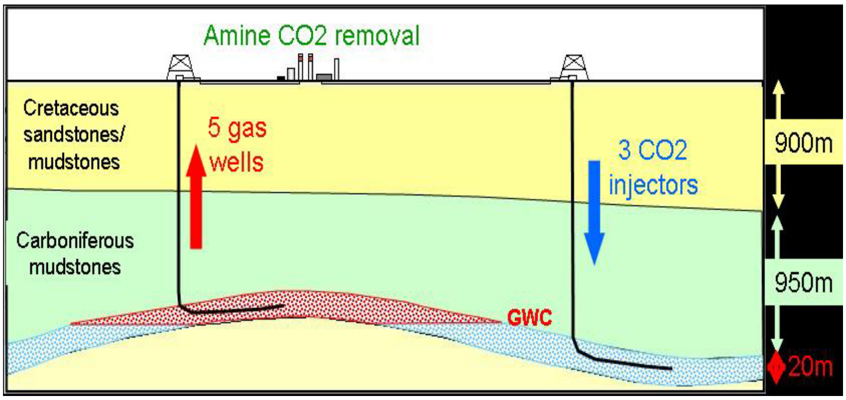

Figure 2: Schematic of Injection Site - Krechba

The CO_2 is injected via three long (1500m) horizontal wells (injecting up to 50mmscfd of CO_2) drilled into the eastern and northern flanks of the main producing field. All injectors and producers have been drilled in a NE/SW direction to intersect the preferred reservoir level fracture orientation (NW/SE) as evidenced from seismic, cores and image logs. Some 75% of the CO_2 has been injected into the two northern injectors, KB502 and KB503 (figure 3).

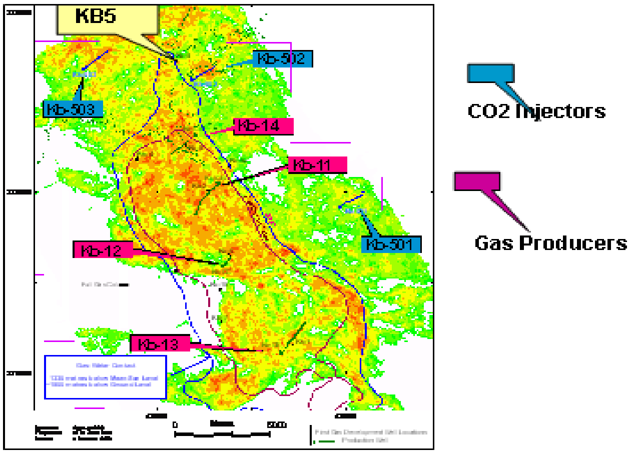

Figure3: Krechba Field Well Locations

The map in figure 3 is based on a seismic extraction of reservoir quality, the darker (red) colours representing better reservoir quality. Recently, CO_2 was sampled in the KB5 observation well some 1.5 km to the NW of the major KB502 injector. A tracer sample injected into KB502 was detected in the KB5 well only 8 months after start of tracer injection, suggesting a rapid movement of the CO_2 between the two wells, most likely along a fracture zone. Initial evaluation based on wellhead and downhole pressure measurements in the KB5 and KB502 wells indicates that the injected CO_2 is remaining within the injection level.

A Joint Industry Project (JIP) was formed in 2004 to evaluate technologies suitable for long term (>1000yrs) verification of CO_2 sequestration through short term (< 15 yrs) monitoring. The In Salah CO_2 Storage Project is a five-year, $30mm, Joint Industry Project (JIP) with participation from the EU and USA (Department of Energy). The key objectives of the JIP are to:

- Demonstrate how short-term monitoring can provide long term assurance on storage security
- Prove the viability of underground CO_2 sequestration as a GHG mitigation option
- Provide a potential framework for regulation of storage and monitoring.

2. Structure of Overall In Salah JIP Monitoring Programme

Before injection commenced at In Salah, a risk assessment review suggested that wellbore integrity and direction of CO_2 migration were the key risks associated with the In Salah storage site and an assessment was then undertaken of the possible technologies that could be deployed to monitor the movement of CO_2 in the subsurface. Initially each technology was placed on a Boston Square in terms of benefit to the JIP vs. the cost to the JIP (Figure 4).

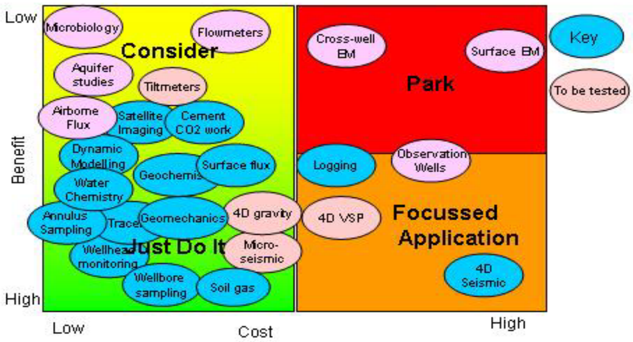

Figure 4: Potential Monitoring Actions for the Krechba site

The X axis shows the cost of the technology to the JIP and the Y axis assesses the benefits to the overall JIP objectives. Some technologies are proven in this environment but others are less mature and have to be evaluated before they can be ranked and deployed. Each quadrant is labeled. Technologies that show high cost and low benefit were dropped from the programme.

All of the proposed monitoring and verification technologies are standard techniques used in oil and gas field exploration and development. Subsequent detailed modeling taking account of the specific subsurface architecture at Krechba, site logistics and the injection conditions resulted in a number of technologies being dropped. For example, the water table at Krechba is at around 105-110m which indicates that surface based monitoring techniques (e.g. soil gas) would be inappropriate. Another technology which was initially considered suitable was electromagnetic monitoring but difficult logistics and the subsurface architecture at Krechba indicated that this technology would be inappropriate at this site.

The key elements of the current monitoring programme ongoing/planned at Krechba are as follows:

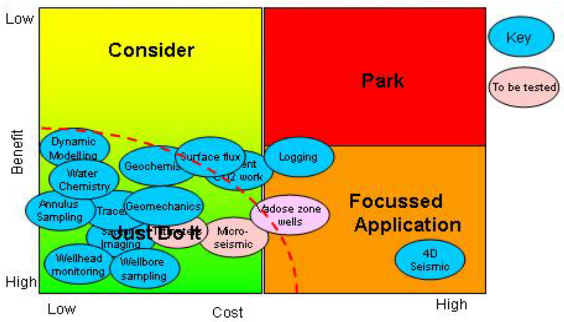

Figure 5: Current Monitoring Programme – Krechba

- 3D Seismic – Northern Krechba
- Micro seismic test well – KB502 area
- Tiltmeters/DGPS – KB501 area
- Satellite Imagery- whole field
- Observation wells to monitor the potable aquifer – central part of field
- Surface Flux and Lineament Analyses
- Wellhead Annulus Monitoring
- Data from new development/water wells

As can be seen, most of these technologies now cluster in the bottom left hand corner of the square but some such as 3D seismic, despite its cost, is still considered a key technology. Furthermore, some technologies have moved onto the priority square since the start of the programme, most notably satellite imagery which was initially considered to be of little value at Krechba but which is now proving to be one of our main tools for trying to assess the subsurface movement of CO_2 at Krechba. The technologies highlighted with blue are considered to require no further testing and are key technologies for use and deployment at Krechba. Those coloured in pink are still considered to require testing to assess their potential benefits – this is particularly the case for microseismic and tiltmeters. Microseismic testing is included as part of the 2008/9 field programme while an array of tiltmeters will be deployed around the KB501 area in early 2009 to calibrate the satellite images.

The In Salah project receives no commercial credit for the CO_2 storage, but if the storage were being regulated, a monitoring programme would be required for compliance. The red dotted line on figure 5 illustrates how agreement could be reached between a developer and a regulator on a site-specific, cost-effective compliance monitoring programme.

Thus the overall monitoring and verification programme has been developed to provide suitable monitoring in the Reservoir, Overburden, Aquifer/Vadose and Surface zones as schematically shown on figure 6.

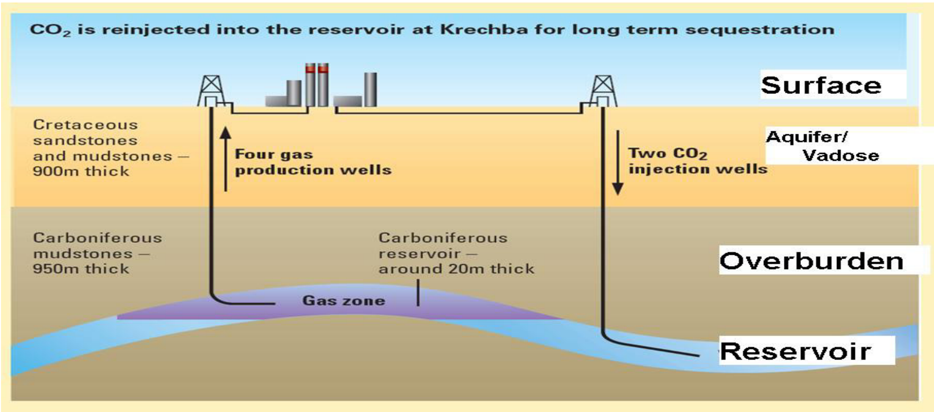

Figure 6: Subdivision of Monitoring Programme

A key part of the monitoring programme is satellite imagery of surface deformations that could facilitate frequent, real-time imaging of CO_2 migration through the storage formation.

3.0 Satellite Imagery

Satellite image data acquired in the first four years of injection show that the ground surface above the three CO_2 injectors is being positively deformed by up to 10 mm per year. While not significant in terms of the local environment, the rate and pattern of surface deformation is being evaluated to provide an understanding of both the subsurface movement of the injected CO_2 and of the geomechanical response to the injection of CO_2 at Krechba. The uplift over the first few years of injection is shown in figure 7, the deep blue areas being those of greatest uplift and the yellow areas being those of subsidence due to production (or erosion in a wadi).

The initial analyses of these data (by LBNL in association with TRE) suggested a strong orientation of the surface deformation in a NW-SE direction (Vasco et al.[1]) and that the CO_2 is moving in the preferred orientation of the fractures at the Krechba reservoir/injection level. The satellite image data also confirms the orientation of possible fractures linking the KB5/KB502 wells based on the very rapid movement (three months) of CO_2 and tracer between the two wells as noted above.

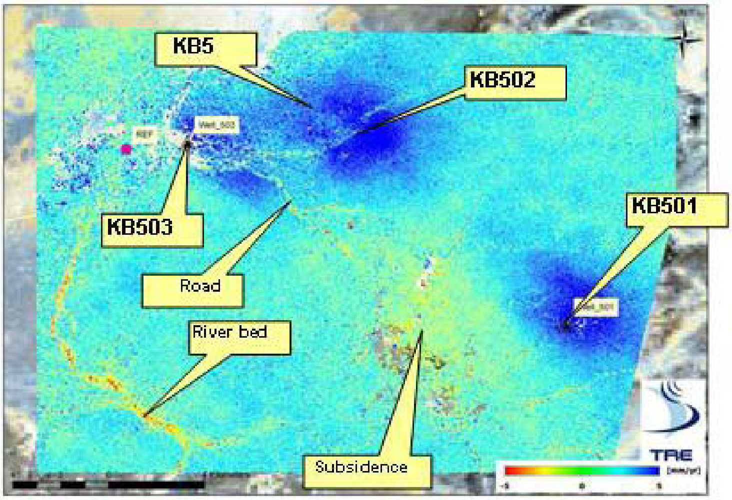

Figure 7: Initial Satellite Image: 2007

Further satellite imaging work done by the Japanese Geological Survey (JGS) and the British Geological Survey (BGS), using the slightly different DSInSAR method[2], confirmed the initial surface deformation analysis and a detail of their work in the region of the KB502 well is shown in figure 8. The dark red areas indicate uplift while the darker blue areas indicate subsidence and the NW-SE orientation of the surface deformation is again very apparent on this image.

While initially considered an unpromising technique for use at Krechba, the match between the ground deformation information and the evidence from subsurface data for the movement of CO_2 in the reservoir is intriguing and requires further investigation. The satellite images have demonstrated the need for Tiltmeters/DGPS (to calibrate the images), microseismic (to check the degree of fracturing) and surface flux monitoring (to assess possible surface leaks in the area of maximum deformation (considered highly unlikely)).

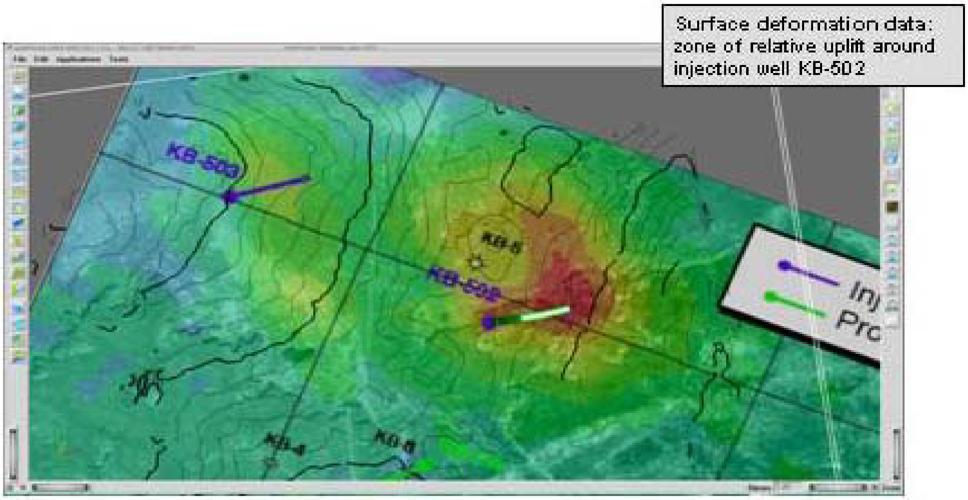

Figure 8: JAPEX/BGS Satellite Image August 2007

The satellite image changes from 2004 to 2007 are shown on figure 9 (using the PSInSAR analysis by TRE and LBNL).

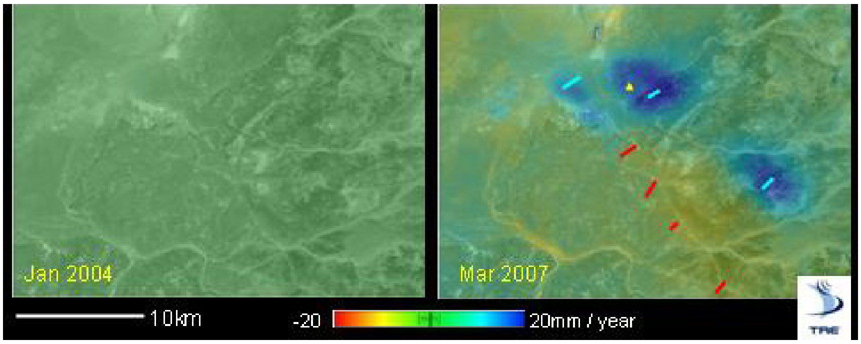

Figure 9: Satellite Images: Jan 2004-March 2007

The quality and rate of acquisition of satellite images over Krechba has recently been increased and images are now collected using RADARSAT2 which collects data every 26 days at a ground surface resolution of 3 m^2. Both overburden geomechanical and seismic data are being incorporated into a detailed overburden model which can be used to predict surface deformation from various amounts of CO_2 injection at Krechba. If this data can be calibrated, then the opportunity exists for the monitoring of CO_2 movement in the subsurface using satellite images at Krechba. With the considerable logistical and other environmental constraints present at the site, such an opportunity would constitute a significant breakthrough.

It is has also been shown that forward and inverse modelling of the satellite deformation data is a valuable approach to monitoring subsurface CO2 injection, and the approach now being considered is shown in figure 10 (courtesy of LBNL, one our JIP partners).

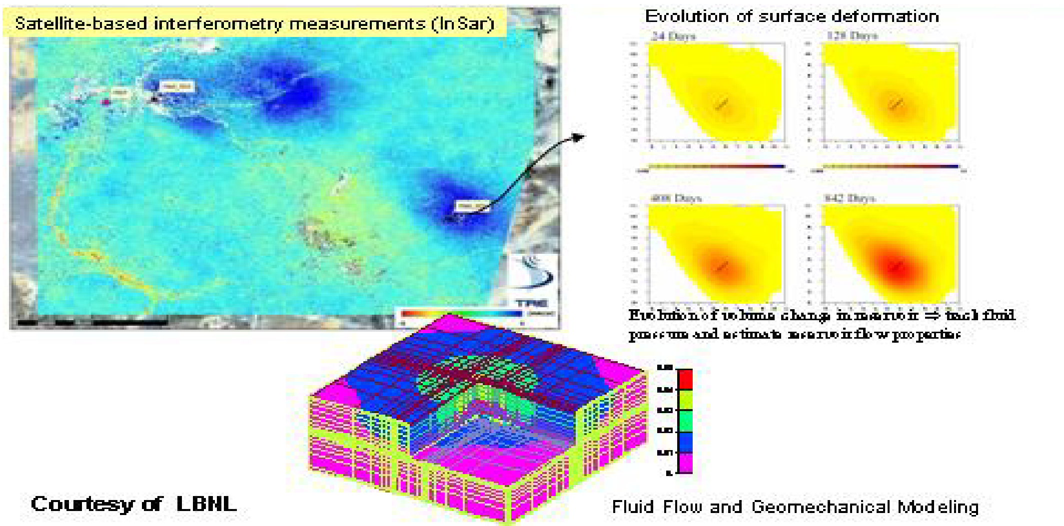

Figure 10: Forward Modelling of CO_2 Movement using Satellite Images

Further work is ongoing to integrate the satellite imagery results with the available 3D seismic and to assist with an assessment of the current Krechba fault model which can then lead to a better understanding of the movement of injected CO_2 at Krechba. Integration of the current satellite data within a Geoprobe project is proving invaluable and an example of this type of integration work is shown on Figure 11 below. Visualisations such as these are now being routinely used to better understand the reservoir and overburden models at Krechba to assist with the monitoring and verification of long term storage of CO_2 at the injection level. Satellite images will continue to play a vital role in this process.

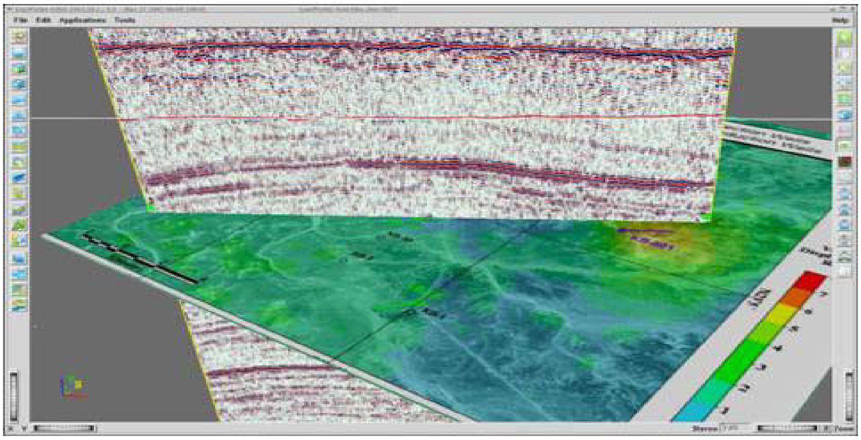

Figure 11: Geoprobe Visualisation of Seismic/Satellite images – Krechba

4. Conclusions and Recommendations

The key insights from the satellite data collected to date are thus as follows:

- Satellite Imagery indicates more ground uplift than anticipated
  - 8-10mm/yr estimated with error of +/- 1 mm/yr
  - This was initially unexpected given depth of injection and the stiffness of the immediate overburden
  - Subsequent detailed modelling shows that this uplift can be explained by poro-elastic response to the increased injection pressure at depth.
- Modelling of the surface response suggests that injection is confined to the aquifer layer
  - however the lateral extent of CO2 is more constrained and seems to be controlled by faults and fractures
- The pattern of uplift suggests migration of CO_2 along the preferred fracture orientation
- Monitoring planned for the near future includes the following technologies
  - Time-lapse seismic
  - Microseismic
  - Satellite imagery
  - Tiltmeters
  - Surface flux and potable aquifer monitoring

For industrial-scale CCS deployment, CO_2 plume monitoring programmes will have to be site-specific, cost-effective and performance-based. Experience at In Salah shows that satellite imagery now has the resolution to be a key monitoring technology for onshore storage.

The In Salah JIP continues to evaluate different monitoring technologies at this industrial-scale sequestration project. In 2009 we plan to acquire a 3D seismic survey in addition to tiltmeter and micro-seismic surveys and observation wells. A key part of the programme is the geomechanics work at the Lawrence Livermore and Lawrence Berkeley National Laboratories that will help to tie the surface observations from satellite to the subsurface movement of CO_2.

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