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A coupled reservoir simulation-geomechanical modelling study of the CO_2 injection-induced ground surface uplift observed at Krechba, In Salah

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Abstract

Building on the previous reservoir simulation study of CO_2 injection at Krechba, a coupled reservoir simulation-geomechanical modelling study was carried out, aiming to match the InSAR surface uplift time series at the three injection wells (KB-501, KB-502 and KB-503) over a 5-year injection period (August 2004 - October 2009). The geomechanical response at the ground surface to subsurface CO_2 injection has been largely reproduced at KB-501; however mixed results were obtained for areas around KB-502 and KB-503. This work suggests that CO_2 has most likely migrated up to the lower caprock around KB-502 from February/March 2006.

Keywords: In Salah CO_2 storage; InSAR surface uplift monitoring; reservoir history matching; coupled geomechanical modelling

1. Introduction

Since August 2004, around one million tonnes of CO_2 per year have been separated from the produced gas streams in the In Salah gas fields and about 70 % of this re-injected back to the subsurface into the aquifer-leg of the Carboniferous sandstone reservoir. The main CO_2 storage aquifer (C10.2) at Krechba is approximately 20-25 m thick at about 1,880 m below the surface. It is overlain by a tight sandstone and siltstone formation (C10.3) of about 20 m in thickness, which is in turn overlain by a 950 m thick formation of Carboniferous Viséan mudstone interbedded with thin dolomite and siltstone layers (Fig. 1a). The C10 formation, together with the lower cap rock (C20.1 – C20.3), form the CO_2 storage

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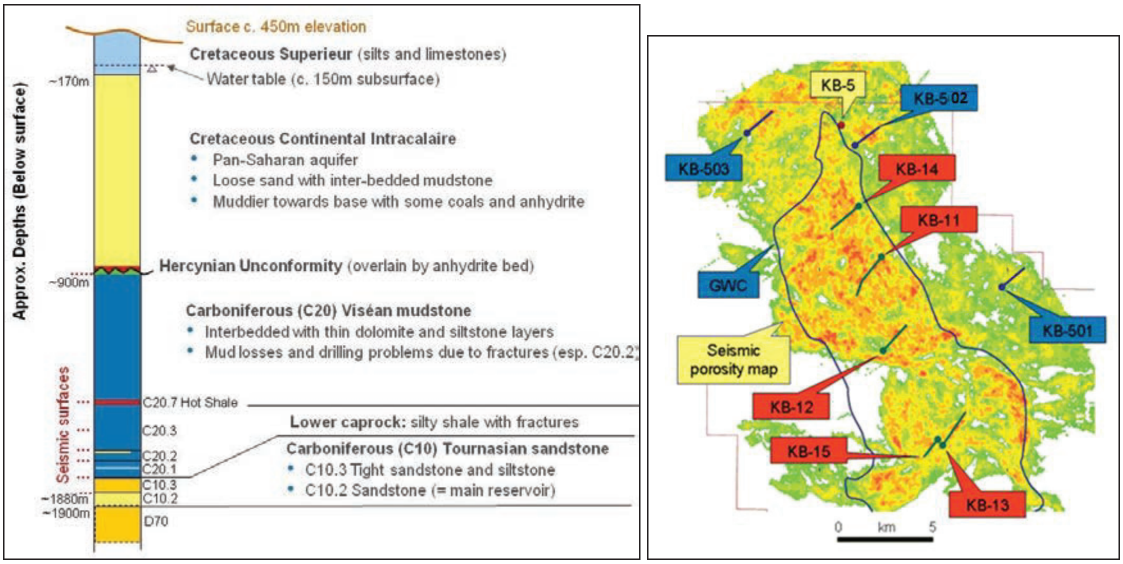
complex. The three horizontal CO_2 injection wells (KB-501, KB-502 and KB-503) were drilled in the aquifer and across the principal open fracture set (Figure 1b). Gas production wells were also drilled in the same direction in the gas reservoir zone.



(a) (b)

Fig. 1. (a) Krechba stratigraphic summary; (b) Krechba field layout showing the locations of the three CO_2 injection wells (KB501, KB502 and KB503) and the production wells (courtesy of the In Salah Gas Joint Industry Project).

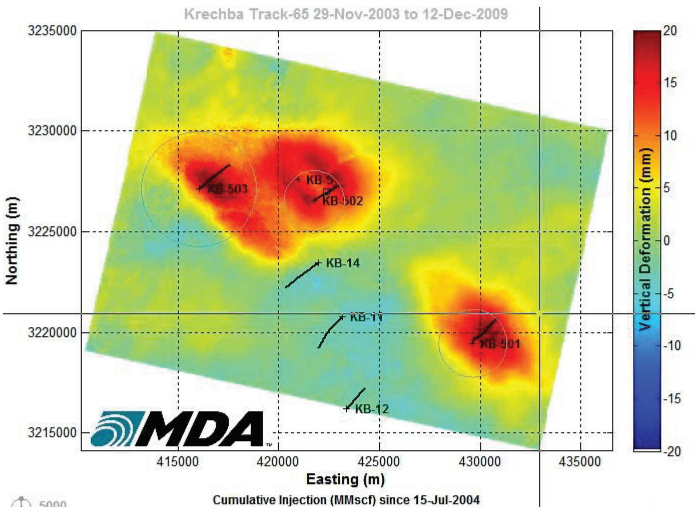


Fig. 2. Surface deformation detected over the CO_2 injection and production wells at Krechba using PSInSAR technique (courtesy of In Salah JIP).

Surface uplift has been detected over all three of the In Salah CO_2 injection wells with corresponding subsidence also observed over the gas production area (Fig. 2). The distinctive two-lobed uplift pattern over KB-502 has attracted much research interest [1-3], as it suggests the tensile opening of a structural discontinuity at depth. In a recent study [3] the authors adopted a holistic approach to match the estimated flowing bottomhole pressure (FBHP) and described the movement of injected CO_2 at KB-502, utilising the current knowledge of the Krechba stress field and time-lapse InSAR surface uplift images. In particular, a c. 5 km long non-sealing fault (zone) with dynamic transmissibility was implemented in the reservoir/overburden model, based upon the fault mapping and inverse modelling work by the In Salah Gas Joint Industry Project (JIP). Two scenarios were considered: 1) lower caprock seal maintained throughout and CO_2 contained within the C10 formation (C10.2 and C10.3); 2) CO_2 migration into the lower caprock has occurred at some stage in 2006.

Building upon the previous reservoir simulation work, the coupled reservoir-geomechanical modelling effort described here aimed at gaining an understanding of the surface response to subsurface CO_2 injection at Krechba. In the current study, only the first scenario was considered for geomechanical modelling.

2. History matching of injection pressure at the three CO_2 injection wells at In Salah

As part of an EU and industry funded CO_2ReMoVe project, a history matching study of the injection pressure at the three injection wells has previously been carried out at Imperial College [4]. The dynamic reservoir/overburden model used was based upon the complex static model provided by the In Salah JIP. The reservoir/overburden model consisted of 5 stratigraphic units (Table 1), and a total of 18 layers. As shown in Fig. 3, the main storage reservoir C10.2 and the overlying tight sandstone formation C10.3 each contains three layers. The next 4 layers up represent C20.1-2. The static model is attributed with stochastically generated permeability and porosity values (Table 1).

It was found that a good over-all match, both in trend and to a less extent the magnitude, to the estimated FBHP (courtesy of In Salah JIP) at KB-501 and KB-503 could be obtained by using only the matrix permeability with some fine-tuning around the wellbore region (Fig. 4a and 4b). A pore volume multiplier of 10,000 at the north boundary of the model domain was applied to represent the pore volume beyond. In the graphs, the CO_2 injection rates are also plotted for cross-reference. It is seen that the pressure peaks are well-correlated with occasional surging in the injection rate. It is further noted that the model over-predicted pressure increases for both wells at around the beginning of 2008.

On the other hand, the injection pressure at KB-502 was matched by incorporating into the reservoir model a pre-existing fault zone (confined to C10.2 and C10.3) which cut across the horizontal borehole with a dynamic fault transmissibility value representing dilation (tensile opening) of the fault zone (Fig. 4c). Tensile opening was believed to have occurred at around November 2005, when the pre-injection stress normal to the fault zone was exceeded by the downhole injection pressure. In the ensuing months (to March 2006), the fault transmissibility grew by approximately 4 orders of magnitude, as a result of sustained CO_2 injection at an increasingly higher rate, so as to keep the model prediction in line with the field FBHP values. Surprisingly, it is noted that the fault became increasingly more conductive over the period March 2006 to July 2007, even when the injection pressure (as well as injection rate) was actually declining. This apparent “anomaly” in the fault transmissibility behaviour has been interpreted as a sign that CO_2 was most likely moving into the lower caprock [4].

The low permeability tight sandstone formation C10.3 (k_v ~ 0.002 mD) is expected to act as an effective buffer zone to the injected CO_2, i.e. CO_2 would be securely contained within the C10 level (mainly C10.2). The simulation results for KB-501 and KB-503 (over the injection period August 2004 - October 2009) appear to support this view. However, C10.3 seems to be not tight enough to prevent injection-induced pressure waves to propagate upwards in to C20.1-2, but no further, as C20.3 (k_v ~10^{-4} mD) offers a much more effective seal.

Table 1. Stochastic reservoir /overburden flow properties provided by the In Salah JIP.

	Mean porosity (std. dev.)	Mean k_h, mD	$Log_{10}(k_h)$ (std. dev.)	k_v/k_h
Shallow Aquifer (Cretaceous)	0.25 (0.2)	1,000	3 (0.5)	0.1
C20.3+ (mudstone)	0.1 (0.01)	0.001	-3 (0.5)	0.1
C20.1-2 (mudstone + silt)	0.05 (0.01)	0.1	-1 (0.5)	0.1
C10.3 (tight sandstone)	0.01 (0.01)	0.02	-1.7 (0.5)	0.1
C10.2 (reservoir sandstone)	Sampled from the In Salah Joint Venture reservoir model			

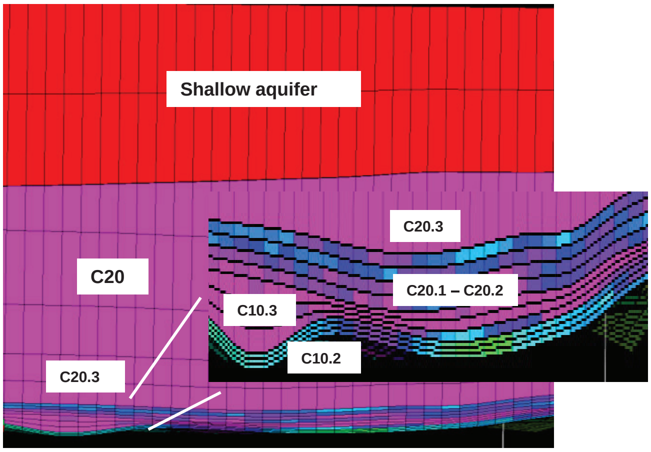


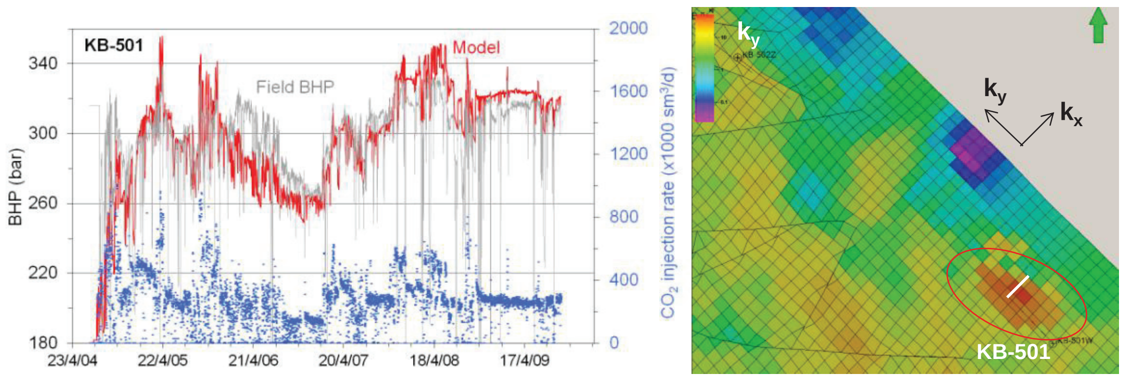
Fig. 3. The ECLIPSE reservoir/overburden model used in the flow simulations in this study.

3. Coupled reservoir-geomechanical modelling

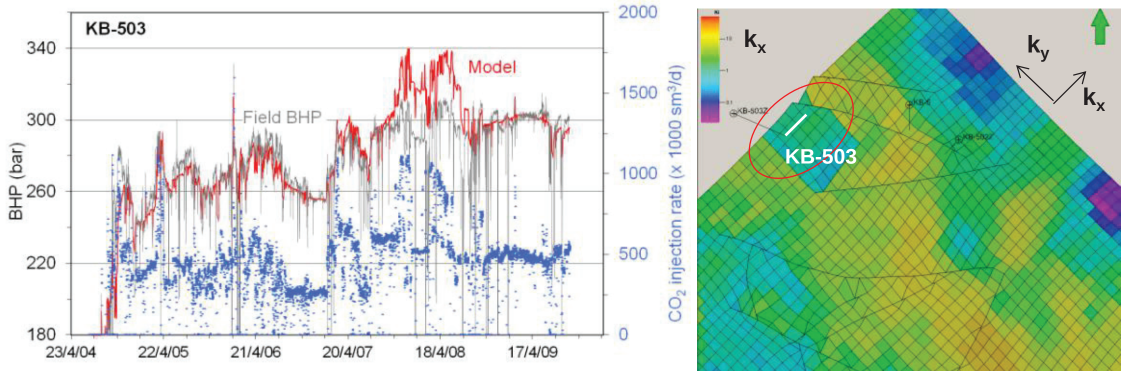
To ensure a seamless coupling with the software used for the flow modelling (ECLIPSE), the geomechanical code VISAGE was chosen. A simple one-way coupling involves importing the calibrated ECLIPSE reservoir model into VISAGE, and augmenting it with over-/under-/side-burdens (only under-/ side-burdens in this study) to minimize boundary effects.

3.1. Krechba gas field elastic properties

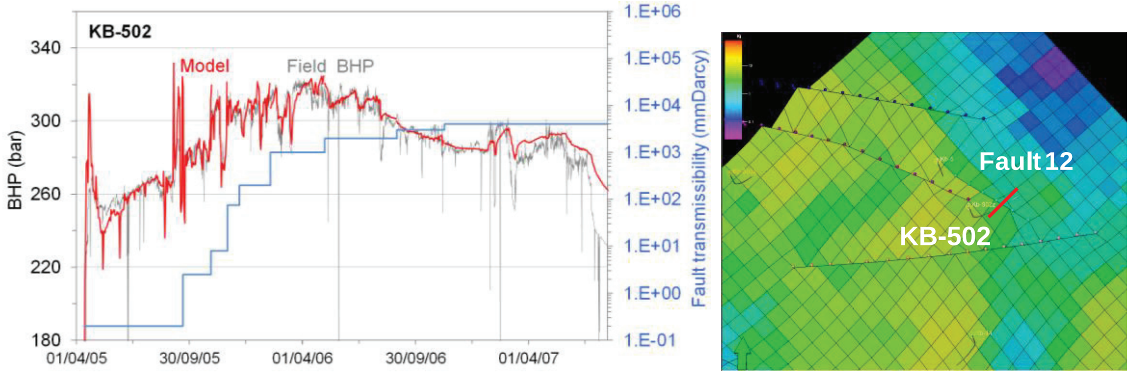
The In Salah JIP geomechanical reference model [5], which features a set of rock elastic properties (Young's Modulus E and Poisson's ratio ν) of the reservoir and over-/ under-burden rocks, was used as the base case. The properties for the Devonian strata (underburden), the main reservoir (C10.2) and the overlying tight sandstone layer (C10.3) are estimated from good quality logs, whereas those for the lower cap rock (C20.1-3), the main caprock and the shallow aquifer are subject to considerable uncertainty (Table 2). Past research has shown that the elastic modulus of the lower caprock has the largest impact on surface subsidence induced by reservoir depletion. Therefore, it was decided to use the Young's Modulus E for the lower part of the lower caprock (C20.1-2) as the main tuning parameter during history matching.



a) KB-501, k_y was multiplied by 3 in the near-wellbore region, with k_x remaining unchanged.



b) KB-503, both k_x (x 2/15) and k_y (x 2/3) were reduced in the near-wellbore region.



c) KB-502, a fault zone (contained in C10.2-3) was implemented in the reservoir model.

Fig. 4. History matching of the CO_2 injection pressure at In Salah.

Table 2. Storage reservoir and under-/over-burden rock elastic properties (In Salah JIP Reference model).

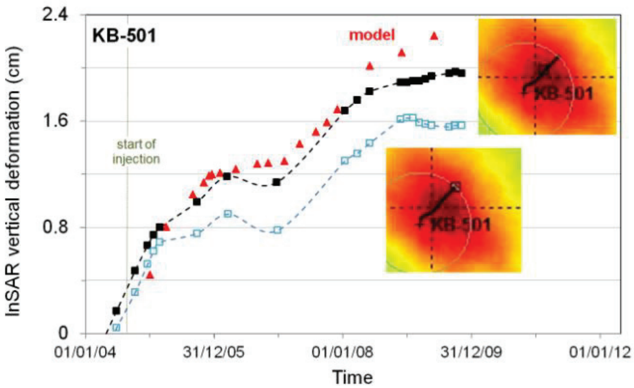
	E, GPa	ν	Comment
Shallow Aquifer (Cretaceous)	3	0.25	very uncertain
C20.3+ (mudstone)	5	0.30	very uncertain
C20.1-2 (mudstone + silt)	2	0.30	very uncertain
	(**18**)		(this study)
C10.3 (tight sandstone)	20	0.25	good logs
C10.2 (reservoir sandstone)	10	0.20	good logs
Devonian (underburden)	15	0.30	good logs

3.2. Geomechanical modelling results

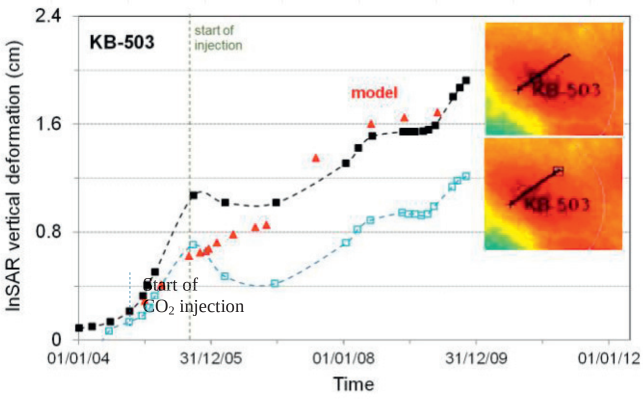
Calibration of the geomechanical model was first carried out by matching the temporal changes in the maximum vertical lift predicted by the model to the InSAR time series for KB-501, which is reasonably far away from the model domain boundary. As shown in Fig. 5a), a fairly good overall match was achieved by using a Young's Modulus of 18 GPa for C20.1-2, which is slightly lower than that of the underlying tight sandstone C10.3 (20 GPa), with other properties remaining unchanged (Table 2). It was noted that the model underestimated the uplift in the early stages, yet overestimated in the later stages of the simulation period (August 2004 – October 2009).

After calibration, the model predictions of the maximum surface uplift for KB-502 and KB-503 were then compared with the corresponding InSAR data. For KB-503 (Fig. 5b), the model failed to reproduce the initial rapid rise in the surface uplift (the reason for this is not clear), but appeared to catch up with the trend in the later stages of the 5-year injection period.

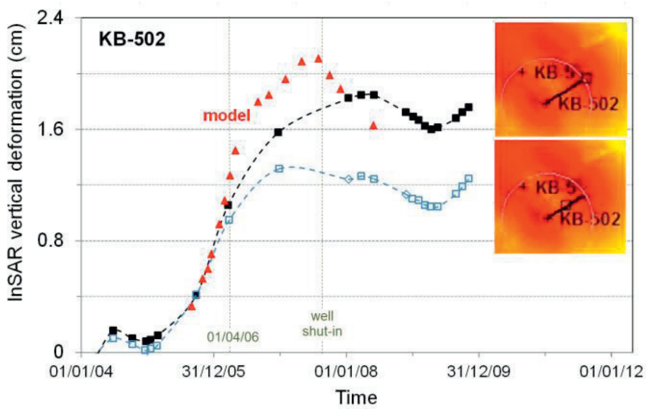
A mixed outcome was also observed at KB-502. As shown in Fig. 5c, the model prediction agreed well with the field data up to February/March 2006, corresponding roughly to the time the two field uplift curves began to diverge (and the emerging of the two-lobed pattern over KB-502 [4]); it then increasingly overestimated the (maximum) surface uplift in the ensuing period to July 2007, followed by a sharp decline when the CO_2 injection was temporarily ceased. The surface uplift picked up again with the resumption of CO_2 injection in the autumn of 2009. Fig. 6 shows a snapshot of the predicted surface uplift (and also the subsidence associated with gas production wells) over the Krechba gas field on 1st April 2006.



a) KB-501



b) KB-503



c) KB-502

Fig. 5. InSAR surface uplift time series (courtesy of the JIP) and the model predictions. The two curves (with different offsets) in each graph corresponding to two marked locations (centre and the right end) along the borehole. Note that, unlike KB-501 and KB-503, larger uplift is found within the two lobes, rather than at the centre, at KB-502.

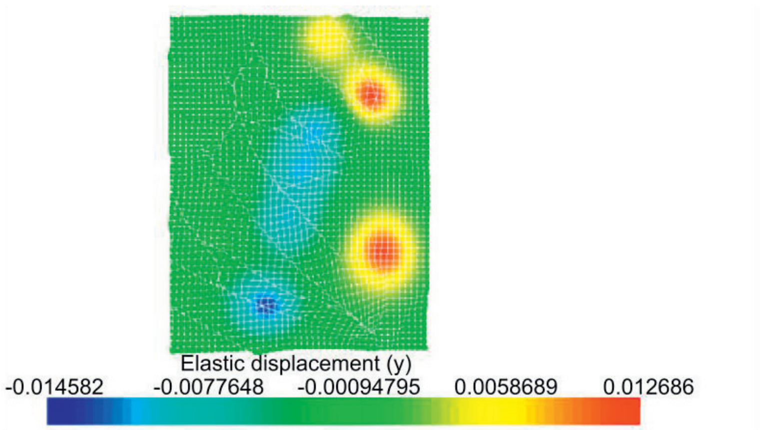


Fig. 6. A snapshot of the predicted surface uplift (positive)/subsidence over the Krechba gas field (April 2006).

4. Discussion and conclusions

Building on the previous reservoir simulation study of CO_2 injection at Krechba, an effort has been made to match the InSAR surface uplift time series at the three injection wells over a 5-year injection period (up to October 2009). The geomechanical response at the ground surface to subsurface CO_2 injection has been largely reproduced at KB-501; however mixed results were obtained for KB-502 and 503.

It has been reported that the observed two-lobed pattern over KB-502 could be reproduced numerically by pressurising a fault/fractured zone with anisotropic elastic properties in the lower caprock (~200 m above C10.2) [2]. Using a 2D plain-strain geomechanical model, Gemmer et al. [5] investigated the impact on the surface uplift by allowing CO_2 injection-induced pressure increase propagating up to a vertical 'fault/fracture zones' in the lower caprock around KB-502 and KB-503. They showed that the predicted surface uplift would be considerably lower, accompanied by an enhanced horizontal displacement which leads to a depression in the vertical surface displacement pattern, when a reduced cohesion (3 MPa), instead of the intact rock cohesion (5 MPa), is used for the fault/fracture zones. Previous reservoir simulation work [4] indicated that this pressurizing of the fault/failure zones in the lower caprock around KB-502 has most likely occurred from around March 2006. The current coupled reservoir simulation-geomechanical modelling results are consistent with these findings. Further work is required to resolve the mismatch between the model predictions and the InSAR data for KB-502 (from March 2006 onwards) and KB-503 (during the first two years).

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