CO_2CARE

CO_2 Site Closure Assessment Research

Grant Agreement number:	256625
Project acronym:	CO_2CARE
Project title:	CO_2 Site Closure Assessment Research
Project number:	256625
Call (part) identifier:	FP7-ENERGY-2010-1
Funding scheme:	Collaborative project
Theme:	Energy 2010
Starting date:	01/01/2011
Duration:	36 month

Deliverable

D4.22 Criteria for decision making in site abandonment

Alexander Kronimus, Geert de Bruin, Jens Wollenweber, Ton Wildenborg, Vincent Vandeweijer, Rob Arts (all TNO), Sam Holloway (BGS)

DOI: 10.2312/GFZ.CO2CARE_2013.002

Submitted: August 2013

Dissemination level: Public

Index of Contents

List of Tables

List of Figures

List of Acronyms

BHP	Bottom hole pressure
CA	Competent Authority
CCS	Carbon Capture and Storage
CO_2	Carbon Dioxide
D4.12	CO_2CARE report, e.g. Deliverable 4.12
EC	European Commission
GD	EC Guidance Document
K12-B6	Well no. 6 at the K12-B site
OSPAR	15 Governments and the European Community mechanism to protect the marine environment of the North-East Atlantic

M1	Milestone (1) defined in the EC Guidance Document 3
MMO	Deviation of modelled and monitored site behaviour (Model-Monitoring Offset)
R1	“R-type” Criteria
RM	Risk Management
SCM	Site Closure Milestone
T3	Technical “T-type” Criterion
WP	Work package within CO_2CARE

Executive Summary

The EC Storage Directive (Directive 2009/31/EC on the geological storage of carbon dioxide) defines conditions for the transfer of a CO_2 storage site to a competent authority (CA). These are:

1) Accordance of monitoring data and model predictions,
2) Absence of leakage,
3) The site is evolving towards long-term stability.

As these criteria are defined at a high level they have to be complemented with more specific risk management and technical criteria that can be applied on an operational level. These risk management and technical criteria are the subject of this report.

The risk management criteria, termed “R-type” criteria, described in this report, have been extracted from a risk management (RM) plan for CO_2 storage site responsibility transfer and abandonment developed in the public CO_2CARE Deliverable D4.12 “Risk management plan supporting site abandonment” (CO_2CARE, 2013a).

Some of these R-type criteria refer to input from models and monitoring measurements. If a parameter is predicted by modelling and measured by monitoring, high-level criterion (2) stated above is of primary application. For risk management related treatment of observed irregularities in such parameters, a traffic light system with an associated workflow has been set up.

This workflow provides an additional set of criteria (technical or “T-type” criteria), specifically relating to condition (2) of the EC Directive. The major goal of the traffic light system is to provide a framework for dealing with offsets of model predictions and monitoring data (MMO, i.e. Model-Monitoring Offset). The three criteria levels (high-level criteria of Directive 2009/31/EC, R-type criteria, T-type criteria) have been connected to each other in order to form a coherent generic set of criteria for transfer of responsibility and abandonment of a CO_2 storage site.

Within the preparation of a risk management plan for K12-B site, CO_2CARE Deliverable D4.6 (CO_2CARE, 2013b), the workflow has thoroughly been evaluated on the K12-B site, a test field to study the behaviour of injected CO_2 in the reservoir and to enhance gas recovery.

The practicability of the proposed traffic light workflow could be demonstrated and it is shown how the traffic light system can support the decision making in CO_2 storage site responsibility transfer and abandonment by presenting an example of how to deal with unpredicted or irregular behaviour of the storage site. The traffic light system is suitable for treating irregularities through all phases of the storage lifetime.

The approach to define criteria leading to the responsibility transfer of the site revealed that, although based upon a generic framework, the definition of such criteria is highly site dependent. Particularly the definition of tolerable model-monitoring deviations and accuracies/precisions of models is ambiguous and requires thorough considerations by the operator of the site and the Competent Authority.

Although the traffic light system was designed for treating irregularities in the final stages of the storage lifetime it is well applicable to the treatment of irregularities in all stages of a storage project.

1. Introduction

Decision making in the post-operational phase by the operator is targeted on minimizing risks demonstrating that the site behaviour is understood and that conditions required to transfer the responsibility for the site to a Competent Authority (CA) according to the EC Storage Directive (Directive 2009/31/EC, EC 2009) have been met. The fulfilment of these general conditions can be demonstrated by complying with a set of more specific criteria, which are the subject of this report. According to Directive 2009/31/EC, the application for responsibility transfer for a site to the CA requires the operator to demonstrate the

1) Accordance of monitoring data and model predictions,
2) Absence of leakage,
3) Site is evolving towards long-term stability.

To be able to demonstrate the fulfilment of these three high-level criteria further more concrete low-level criteria applicable on an operational level are required. All of the three fundamental criteria mentioned above, particularly condition (2) rely on monitoring data and models. Monitoring and/or model data are the key outcomes to demonstrate the understanding of site behaviour. By developing a risk management (RM) plan within the scope of CO_2CARE (CO_2CARE D4.12, 2013a) a milestone chart specifically relating to each of the three fundamental criteria has been shaped (called Site Closure Milestones "SCM"). The criteria derived from the risk management (RM) plan are termed **"R-type" criteria**.

In order to assess whether the R-type criteria are met, a traffic light system is set up to support decision making during and after closure of the storage site (cessation of injection). The traffic light system establishes whether or not the monitoring and modelling data are in compliance. The criteria derived from this traffic light system are **"T-type" criteria**.

Table 1 provides an overview of the different criteria and milestones used in this study. The different phases of a CO_2 storage site project and how those are connected to sub-phases and different milestones are illustrated in Figure 1.

Table 1. List of used milestones and criteria and their abbreviation

Abbreviation	Description
M1	Milestones as defined in EC Guidance Document 3 (GD3)
SCM1	Site Closure Milestones of the risk management plan as defined in CO_2Care D4.12
R1	"R-type" Criteria; Criteria derived from Risk Management Plan
T1	"T-type" Criteria; Criteria derived from Traffic Light system

As T-type (and also R-type) criteria are site-specific and are currently hard to define, this study follows a bottom-up strategy by defining (Section 3) and applying those technical criteria to the K12-B site, a current CO_2 injection site in the Dutch sector of the North Sea (Section 4). A brief introduction to the site is provided in the Appendix.

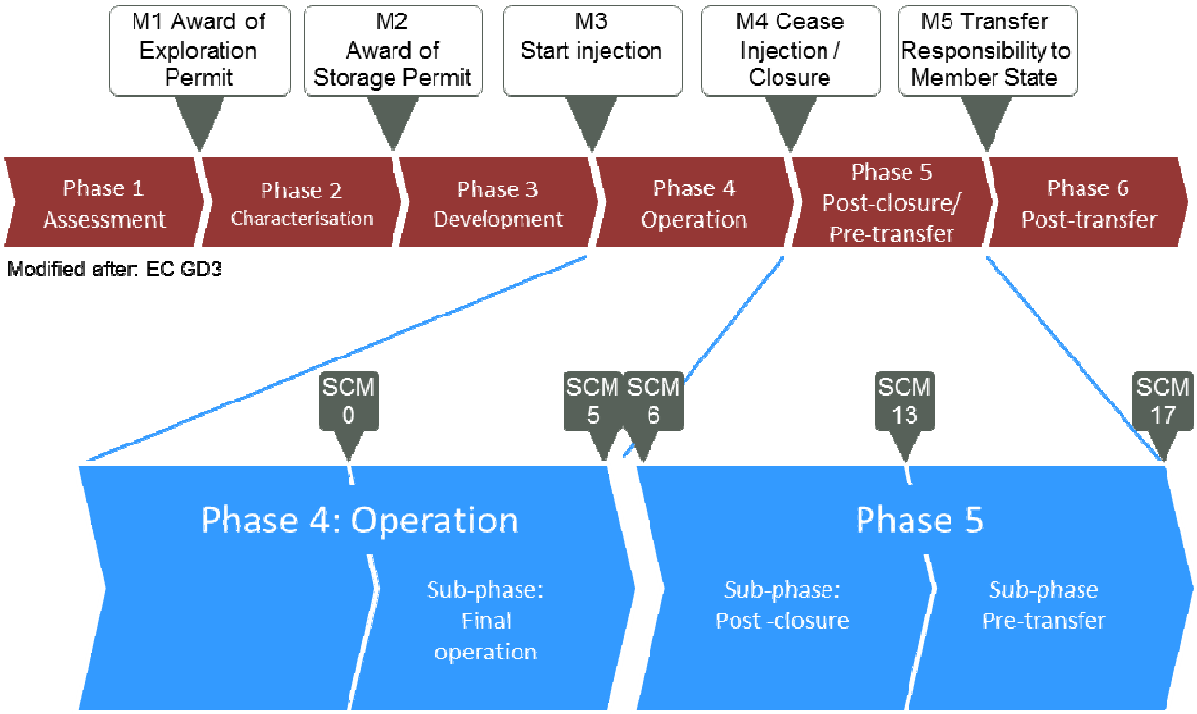

Figure 1. Timeline for CO_2 storage site closure risk management modified after EC Guidance Document 3, closure developed in CO_2CARE Deliverable D4.12 (CO_2CARE, 2013a). M=milestone defined in EC Guidance Document 3 (EC, 2011), SCM= New defined Site-Closure Milestones for risk management of CO_2 storage site

1.1. Definition of "irregular site behaviour" and "significant irregularity"

The EC storage directive states that if significant irregularities occur during the storage process, corrective measures specified in a risk management (RM) plan have to be taken in order to ensure the safety of the site. According to the EC Storage Directive Article 3 (17) a "significant irregularity" is defined as any irregularity during the injection, post-injection/pre-closure or post-closure phase, which pose a risk of leakage or implies a risk to the environment or humans.

Hence, irregular site behaviour can be defined as a state or evolution of the site which is deviating from the predicted regular behaviour. Parameters or indicators of regular or irregular behaviour need to be identified (like pressure or plume extent) and one or more threshold values are to be defined for verifying regular or irregular behaviour. A priori, it is not clearly technically specified what counts as irregularity and which deviations of the project plan (e.g. Monitoring-Model-Conformity) or uncertainty ranges (e.g. for models) are acceptable.

These specifications need to be defined by the responsible operator and Competent Authority (CA) and will depend highly on the characteristics of each specific site, as stated in EC Guidance Document 3 (EC GD3): "*The choice of the percentage (of monitoring-modelling offset) would be determined by the CA and different ranges of tolerances can be specified for each particular measured parameter in order to determine conformity. The CA should specify the applicable percentages for various parameters for each storage site at the time of the storage permit, taking account of site specific characteristics.*"

In practice, it can be expected that the operator will propose offset percentages for each performance indicator, which will then be agreed upon with the CA.

2. Risk management plan

2.1 Criteria based on the risk management plan (R-type criteria)

The risk management plan described in CO_2CARE Deliverable D4.12 (CO_2CARE, 2013a) contains a set of criteria related to the fundamental criteria demanded by the Storage Directive (EC, 2009). The latter are mainly targeting the transfer of responsibility to a competent authority (CA).

In D4.12, a Site Closure Milestone system (SCM) has been set up (Table 2). The deliverable is allocating the milestones to the criteria of the EC Storage Directive in the following way:

1) Absence of leakage/significant risks: Milestones SCM10 and SCM12
2) Conformity of monitoring data and model predictions: By reaching milestone SCM8
3) Site evolvement to a long-term stability: Milestone SCM11

The criteria extracted from the risk management (RM) plan (R-type criteria), including criteria enlisted in the Guidance Document 3 of the EC Storage Directive (EC, 2011), are provided in the following and listed in Table 3).

2.2 Absence of leakage

Milestones SCM10 and SCM12 encompass the following criteria:

- Pressure evolution according to the reservoir models (R1),
- No detectable indication of leakage by monitoring measures (R2),
- Evidence for the location of the CO_2-plume within the storage site by periodic seismic surveys or other appropriate measures (R3),
- Leakage has not been detected for the last 10 years, including the operational phase (R4),
- Well integrity is checked directly before abandonment according to best practices (R5).

2.3 Conformity of monitoring data and model predictions

Milestones SCM7 and SCM8 require that

- Model recalibration iteration loop is ending, i.e. model recalibration is not required any more (R6),
- Model recalibration iteration loop ended at least five years ago (R7).

Table 2. Proposed site-closure milestone chart leading to the transfer of responsibility according to Article 18, EC Storage Directive (CO_2CARE, 2013a)

Site-Closure Milestone (SCM)	Description	Sub-Phase	Phase/Moment
0	Specify models and monitoring selected for conformity check	Final operational	Operational
1	Check model/monitoring conformity during final operational phase; if necessary update models		
2	Provisional post-closure plan updated		
3	Final (updated) post-closure plan submitted		
4	Final (updated) post-closure plan approved		
5	Site closure	-	Site closure
6	Optional update of risk management plan	Post-closure	Post-closure/Pre-transfer
7	Model check-update loop terminates		
8	Models and monitoring data are within acceptable conformance after M7 has been reached without significant adjustment (EC GD3 proposes a minimum period of five years)		
9	Optional final update of risk management plan		
10	Evidence of absence of leakage presented to CA		
11	Effectiveness of storage concept: Evolution to long-term stability demonstrated		
11a	Pressure evolution demonstrated to match model prediction		
11b	Plume movement is demonstrated to be an acceptable match to model predictions (within tolerances)		
11c	Optional verification of other parameters/features related to the storage concept		
12	Final wellbore check before abandonment (final well logging)		
13	(Draft) Report for transfer of responsibility submitted	Pre-transfer	
14	Report approved		
15	Surface facilities removed		
16	Well abandonment accepted		
17	Transfer of responsibility approved and accomplished	-	Site transfer

2.4 Site evolvement towards long-term stability

SCM 11 requires

- Pressure development to an equilibrium pressure and according to models (R8),
- Plume movement is matching model predictions (R9),

- Plume is not moving out of the reservoir, confirmed by modelling and monitoring (R10),
- Optional verification of other parameters/features related to the storage concept (R11).

R11 is specifically related to the confirmation of the envisaged storage concept. Furthermore, enhanced risks of the storage system in question, e.g. a large number of wells, are to be covered by those additional measures. Another measure may be the modelling of mineralization, in case this was part of the storage concept.
The criteria R1 to R11 represent a specification of the three fundamental criteria demanded by Directive 2009/31/EC. This set of criteria can be applied on an operational level. However, the criteria provide no framework for treating offsets of monitoring and model data (MMO, i.e. “Model-Monitoring Offset”). Such a framework is provided in the next chapter.

Table 3. List of the criteria derived from Risk Management Plan

R-type criteria	Description of criteria	EC requirements and Site Closure Milestones (SCM)	Sub-Phase
R1	Pressure evolution conforms to the reservoir models	Absence of leakage (SCM10 & SCM12)	Post-closure
R2	No detectable indication of leakage by monitoring measures		
R3	Evidence for the location of the CO_2-plume within the storage site by periodic seismic surveys or other appropriate measures		
R4	Leakage has not been detected for at least 10 years, this period may include the operational phase		
R5	Well integrity is checked directly before abandonment according to best practices		
R6	Model recalibration iteration loop is ending, i.e. model recalibration is not required any more	Conformity of monitoring data and model predictions (SCM7 & SCM8)	
R7	Model recalibration iteration loop ended at least five years ago		
R8	Pressure is developing towards an equilibrium pressure and according to models	Site evolvement towards long-term stability (SCM11)	
R9	Plume movement is matching model predictions		
R10	Plume is not moving out of the storage site, confirmed by modelling and monitoring		
R11	Optional verification of other parameters/features related to the storage concept		

In order to assess whether certain R-type criteria are met, a traffic light system, explained in the next section, is set up. The traffic light system establishes whether or not the monitoring and modelling data are in compliance. Figure 2 illustrates the high level criteria of the EC

Storage Directive, the associated R-type criteria and which T-type criteria should be assessed based on this traffic light system.

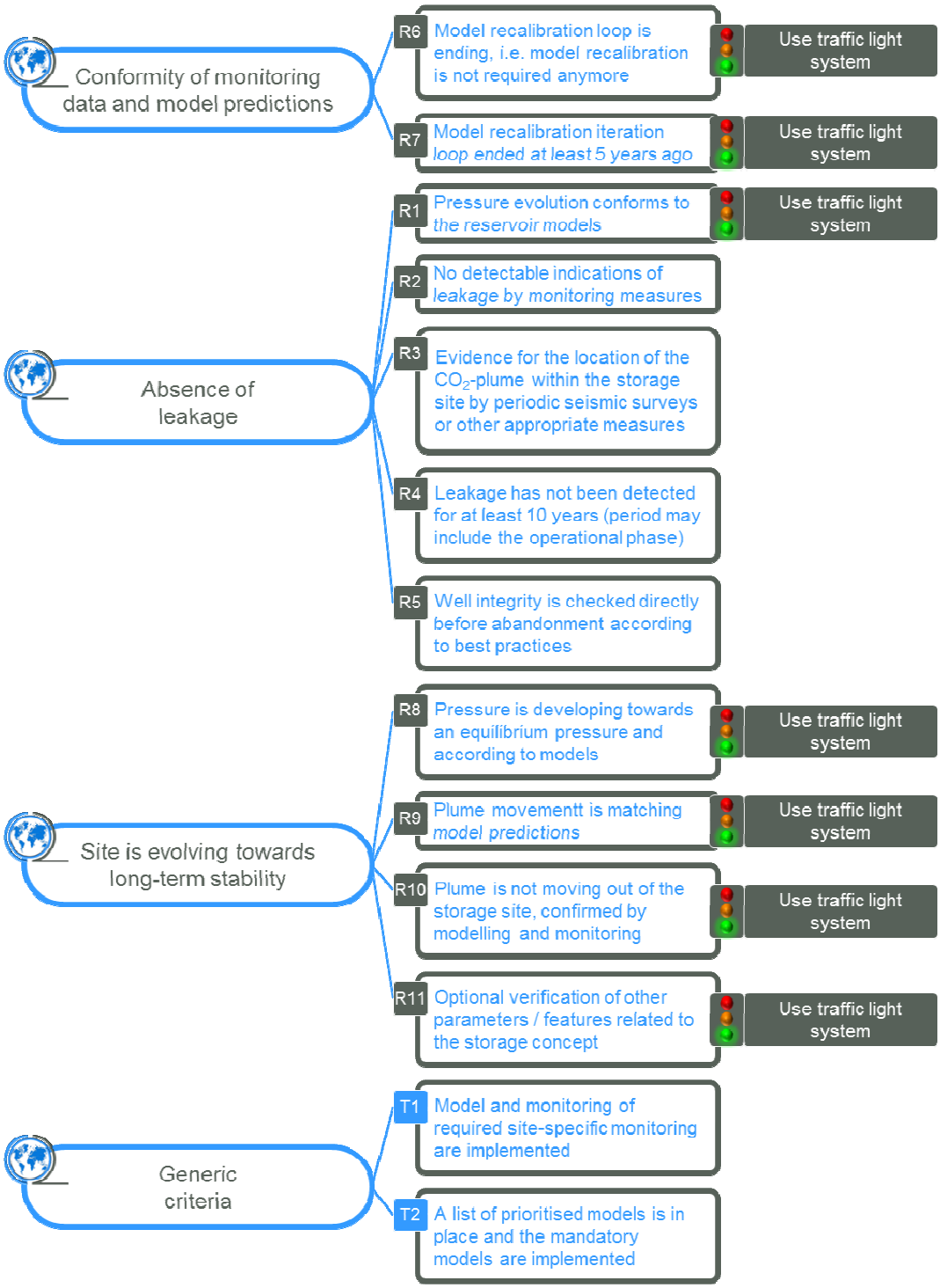

Figure 2. List of criteria for post-operational decision making and responsibility transfer as well as the interconnection between the fundamental, R-type criteria, and the traffic light system

3. Traffic Light System to assess Model-Monitoring Offset (MMO)

3.1 Offset of model and monitoring data (MMO)

Criterion 2 of Directive 2009/31/EC (accordance of monitoring data and model predictions) directly refers to possible offsets (differences) between modelled and monitored data (MMO, i.e. “Model-Monitoring Offset”) when considering the conformity of monitoring results with predictions from modelling of the storage site. This is also discussed in the Risk Management plan described in CO_2CARE Deliverable D4.22.

The other two fundamental criteria (absence of significant risks, site evolvement to a stable situation) also - at least partly - rely on monitoring and model data. Thus, MMO is a very crucial issue in decision making; it is an important goal of this study to define criteria in relation to MMO in order to enable the treatment of such offsets. For this purpose a traffic light decision support system has been set up.

3.2 Set-up of a traffic light system

Figure 3 depicts the flow diagram of the proposed traffic light system. The system consist of a decision workflow determining the condition (state) by which the abandoned site in question is characterized. Three different states are foreseen:

1) Status green: MMO of all parameters are within tolerance, i.e. the site is in a regular and expected condition;
2) Status orange: MMO of one or more parameters are off tolerance; the operator has to prove whether the models in question have to be recalibrated or irregular site behaviour is present; this involves a discussion between operator, experts and the CA;
3) Status red: Irregular site behaviour is present; additional monitoring, counter measures, and mitigation measures have to be applied.

Additionally, there are two levels to which the status can apply: 1): The **site** level and 2) the **parameter** level. At any moment in time in the post-closure/pre-transfer phase (see Figure 1), exactly one status applies on the site level and one for each parameter on the parameter’s level, respectively. There is an increasing risk in the order status green – status orange – status red. **The status of the highest risk on the parameters’ level determines the status valid on the site level**. For instance, if one parameter subject to monitoring and modelling is set to orange and the rest of the parameters to green, the site’s status is set to orange. If one parameter was set to status red, the site’s status would be red as well.

Decision nodes involving criteria are part of the underlying workflow. These criteria are extracted in the following by a step-by-step explanation of the scheme shown in Figure 3 and are summarised in Paragraph 3.3. It is important to note this scheme is to be applied for any parameter subject to modelling and monitoring. This implies that

1) There has to be list of monitored parameters which are used in evaluating the conformity of monitored and modelled behaviour. Likely, not all monitored parameters are being modelled,

2) There has to be a list of **mandatory and optional models**.

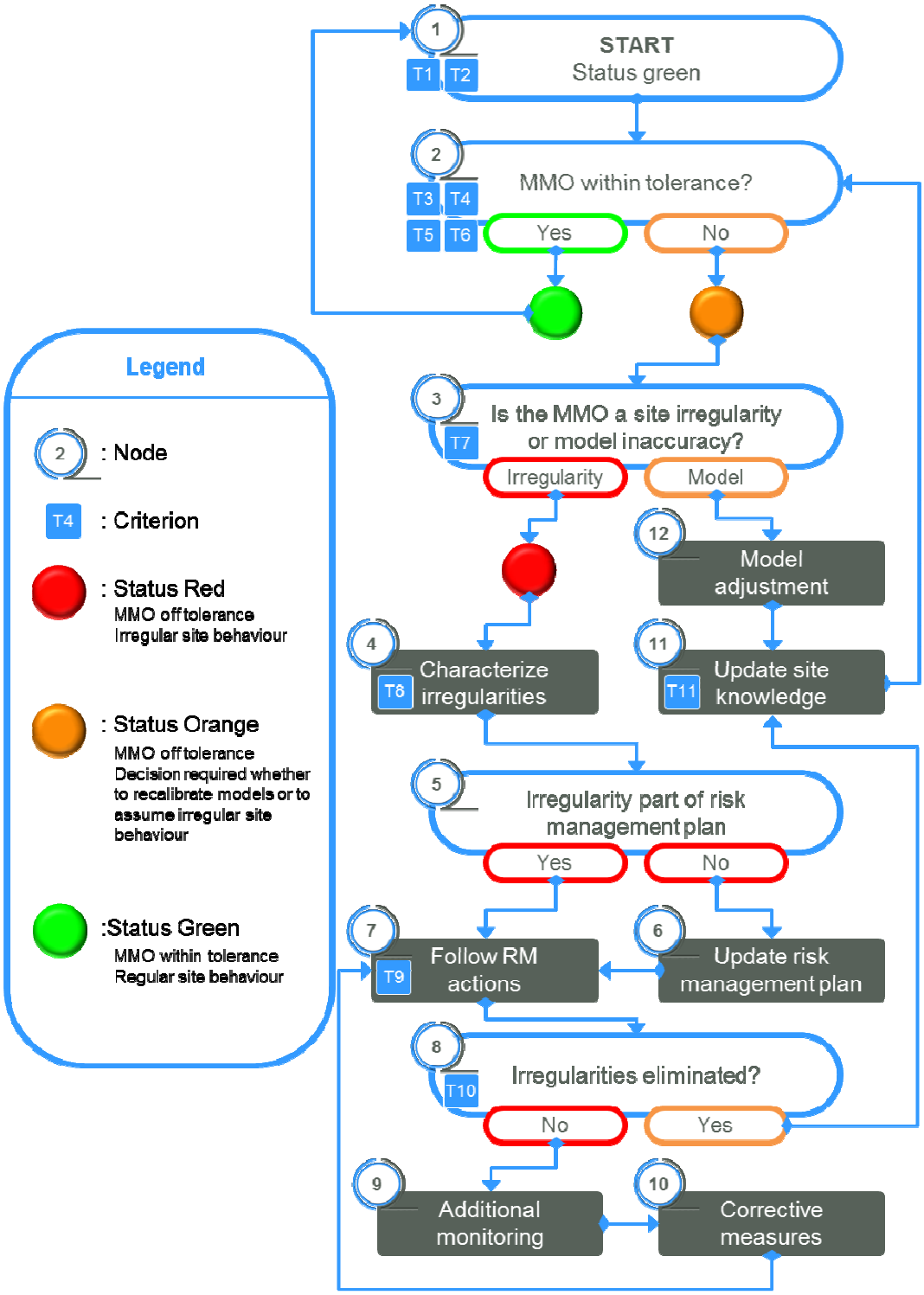

Figure 3. Flow diagram of the traffic light system for risk-related decision making in the post-closure sub-phase and definition of the three risk priorities (status red, orange and green). MMO= Model-Monitoring Offset; note that the Storage Directive exclusively refers to 'significant irregularities' instead of 'irregularities'

The presence and practical implementation of required (mandatory) site-specific monitoring parameters subject to modelling and monitoring (Criterion T1) and a prioritisation of models - mandatory and optional – (Criterion T2) are two important criteria for decision making with respect to risk management and the transfer of responsibility (see also Table 4). These criteria are not applicable per parameter, but refer to the list of parameters and models as a whole. Definition of required models and parameters is part of the site-specific risk assessment and monitoring plan defined in the Characterisation phase of a CO_2 storage project (Phase 3 in Figure 1)

3.3 Criteria deviated from the traffic light system (T-type criteria)

In this section of the report, the scheme depicted in Figure 3 is explained node by node while criteria for decision making are extracted (Table 4). The scheme has to be applied **independently for any parameter subject to monitoring and modelling** within the scope of a storage project.

Table 4. List of the criteria derived from the traffic light approach (T-type criteria).

Crit.	Description	General Criterion
T1	Models and monitoring of required site-specific monitoring parameters are implemented	yes
T2	A list of prioritised models is in place and the mandatory models are implemented	yes
T3	Duration of the time interval to check for MMO	no
T4	Relative amount of the tolerable MMO	no
T5	Accuracy/precision of monitoring technique	no
T6	Accuracy/precision of models	no
T7	Does a gathered MMO refer to site irregularity or is model recalibration required?	no
T8	In case of site failure: Are the primary and all connected irregularities identified?	no
T9	In case of site failure: are all required RM measures ready to be applied?	no
T10	Are the irregularities eliminated by the RM measures applied?	no
T11	Is there data to improve the site knowledge?	no

<u>Node 1</u> (Start)

At the beginning of the post-operational phase status green is assumed for all parameters. Prerequisite is the fulfilment of criteria T1 and T2 as defined above (Table 4).

<u>Node 2</u> (MMO within tolerance)

Here, the decision whether the MMO of the parameter in question is off tolerance has to be made. This involves two criteria:

- Definition of the time interval to check for MMO (T3), and
- The relative amount of the tolerable MMO (T4).

The definition of the time interval depends on the practical and economic feasibility of the required measurements. For instance, wellhead pressures can be measured several times per hour by using automated measurement recording systems. The interval for performing 3D seismic surveys may be measured in years, while data from permanent passive seismic surveys may be gathered on a daily basis. Another important factor for determining an appropriate time interval is **safety and risk**. The higher a risk factor subject to monitoring and modelling, the higher should be the frequency to check for MMO. For decision support, there are two additional criteria to be applied:

- Accuracy/precision of the monitoring technique applied (T5),
- Accuracy/precision of the model(s) applied (T6).

The relative amount of a tolerable offset between monitoring and model data is highly dependent on the site properties and consequently has to be defined at the individual project level. For some parameters it might be difficult to define a tolerable offset at all. Assuming the MMO is within tolerances, the workflow loops back to node 1. Otherwise the state of the parameter in question will be set to orange and the workflow will continue with node 3.

Node 3 (Is the MMO a site irregularity or model inaccuracy?)

By entering node 3 the state of the parameter in question is orange, as it is not clear whether the site is behaving irregularly or whether the underlying model(s) have to be recalibrated. Here, it has to be noted again that the site's risk state is determined by the highest risk state of any of the parameters subject to monitoring and modelling. As the state of the parameter in question is orange, by entering node 3, the site's state is orange **at least**.

At node 3 the decision has to be made, whether the detected MMO refers to an irregular site behaviour or the requirement for model recalibration; this decision represents criterion T7. When using multiple models, a model probability evaluation tool based on comparison of measurements and model computations can be used for decision support (Nepveu et al., 2010). Such a tool, focused on post-operational activities, has been developed in WP4, Deliverable D4.4 (CO_2CARE, 2012). The decision outcome requires an evaluation by the operator, supported by experts and the CA. If it is decided that the cause of the offset is that the model(s) require recalibration the workflow would continue to node 12. Otherwise, irregular site behaviour has to be assumed. In the latter case, state red would be applied to the parameter and consequently to the site and the workflow would continue to node 4.

Node 4 (Characterize irregularities)

By entering node 4, the site is in condition red, indicating site failure. This node demands the identification of all irregularities, including secondary irregularities. For instance, if the identified primary irregularity was leakage through a fault, there may be further associated irregularities such as groundwater contamination. Node 4 connects to the criterion whether the primary irregularity and all connected irregularities are identified (T8). The workflow continues with node 5.

Node 5 (Irregularity part of risk management plan?)

Node 5 refers to the decision whether the identified irregularities are part of the risk assessment and risk management (RM) plan. This should be the case, providing the risk assessment procedure has been undertaken appropriately. However, in the unlikely case of an irregularity not considered by the existing risk assessment, the workflow continues with node 6 and otherwise with moves to node 7.

Node 6 (Update risk management plan)

In case of an irregularity not considered by the existing risk assessment, the RM plan has to be updated, in order to include a suitable portfolio of monitoring, counter and remediation measures (=RM measures).

Node 7 (Follow risk management actions)

Entering node 7 requires the fulfilment of criterion T9, representing the conclusion that all RM measures required for the treatment of all identified irregularities are ready to be applied (T9).

Node 8 (Irregularities eliminated?)

This node involves the decision on whether all irregularities have been eliminated, representing criterion T10. If not, the workflow will loop back to node 7. In theory, this may be an iterative process. In cases where all irregularities have been eliminated, the workflow continues with node 11.

Node 9 (additional monitoring)

According to the RM plan, additional monitoring measures have to be applied, enabling the evaluation of the effectiveness of counter and remediation measures executed within the scope of node 10.

Node 10 (corrective measures)

This node refers to the application of counter measures to eliminate the irregularities detected. This may involve e.g. repairing a well head after failure.

While counter measures are directed to the elimination of irregularities, remediation measures are targeted on the repair of damages, which can, for instance, refer to environmental compartments. If e.g. an agricultural area has been affected by displaced brine, appropriate measures have to be taken to remediate the damages.

Node 11 (update site knowledge)

Information gathered during model fitting and recalibration as well as by treatments of site irregularities may help to

- improve understanding of the site behaviour,
- improve risk management,
- mitigate risks,
- provide information to support the demonstration of the fulfilment of the fundamental criteria required for a transfer of responsibility ofr the storage site to the CA according to the EC storage directive.

Criterion T11 represents the decision on how newly gained information can be used to enhance the site knowledge. After updating the site knowledge, the workflow loops back to node 2 and depending on the decision outcome connected to this node, the parameter's state will be set to orange or green.

Node 12 (Model adjustment)

If, at node 3, the decision is made that a detected MMO off tolerance relates to the requirement for a model recalibration, this will be conducted within node 12. Thereafter, the workflow continues with node 11, as described above.

3.4 Relation between R- and T- type criteria

The criteria set derived from the RM plan (R-type criteria) is related to the condition of a storage site as a whole while the application of the traffic light system deals with discrete parameters.

The criteria implemented in the traffic light system (T-type criteria) provide more detail for the evaluation of MMO and how to proceed after detection of significant offsets between monitoring data and model predictions.

Consequently, the T-criteria represent a subset of all R-criteria referring to **modelled and monitored parameters**. The T-types act as a decision driver. If the traffic light system relying on the T-criteria is on status green, the corresponding R-criteria is fulfilled. As pointed out in Section 3.3, the T-criteria have to be differentiated between generic (T1, T2) and parameter-specific ones (T3-T11). The combined criteria list and the connection between the high-level criteria of the EC storage directive, the R- and T-criteria is shown in Figure 2. It has to be noted that the T-types are parameter-specific. For instance, criterion R1, representing the reservoir pressure requires the application of exactly one traffic light system (assuming only one reservoir model is used).

In contrast, criterion R6 refers to all models applied for risk management. Therefore, one traffic light system has to be applied for each parameter subject to monitoring and modelling within the scope of the storage project in question. Only when all traffic light systems connected to criterion R6 are on status green, is the R-criteria fulfilled.

Criterion T1 encompasses the application of required monitoring and modelling measures and T2 the prioritisation of the modelling approaches, i.e. both mandatory and optional models. The arrangement of these criteria (i.e. T1 and T2) is highly site-specific and influences all other criteria. Reservoir modelling is mandatory in any case. Criterion R11, targeting the verification of the match between site evolution and the envisaged storage concept is

therefore site-dependent as well. All T-type parameters have to be evaluated based on site-specific characteristics, in particular criteria T1-T7, connected to the tolerable MMO, accuracy and precision of modelling and monitoring measures applied and the decision whether a MMO is due to site failure or the need for model recalibration.

The following Section 4 summarizes the evaluation of the developed traffic light system on the K12-B site, which was performed earlier within CO_2CARE. K12-B is a current CO_2 injection site in the Dutch Sector of the North Sea. For detailed information on K12-B and its detailed risk assessment study please refer to CO_2CARE D4.6 “Plan and risk management for abandonment of the K12-B site” (CO_2CARE, 2013b).

4. Traffic light system evaluation on K12-B

In this section of the report we present an evaluation of the workflow for risk management in the final stages of the CO_2 storage project life cycle, conducted within CO_2CARE Deliverable D4.6 “Plan and risk management for abandonment of the K12-B site” (CO_2CARE, 2013b). We evaluate the practicability of the proposed traffic light workflow, demonstrate how the traffic light system can support the decision making in CO_2 storage site closure and show how to deal with a site-irregularity. A brief introduction to the K12-B site is provided in the Appendix. For detailed K12-B site information please refer to CO_2CARE D4.6 (CO_2CARE, 2013b).

Intermezzo

The CO_2 injection activities at K12-B are regulated under a gas production license and do not have to comply with the transposed rules originating from the EC CO_2 Storage Directive (2009/31/EC). However, for this study it is assumed hypothetically that the CO_2 injection and storage activities have to comply with the rules in the CO_2 Storage Directive.

The work presented here particularly focuses on the requirements for transferring responsibility for the site to the State after the definite cessation of the CO_2 injection activities. Some limited period of time may elapse after the end of injection operations before the transfer of responsibility.

The injection pilot facility at K12-B is still in the operational mode and it is not clear when the injection activities will definitely stop. For this study we assume that the pilot is in the final operational stage.

The criteria for decision making will be evaluated on the basis of the information gathered up to and including 2009. In reality all simulation and monitoring data acquired until and in the post-closure pre-transfer should be taken into account.

The conformity of modelling with monitoring is an essential requirement of Directive 2009/31/EC. We will focus on the model-monitoring conformity of the pressures (although other monitoring data is also available for K12-B). The gas production history proved that the field consists of 4 compartments that are not in pressure communication and act as volumetric reservoirs (sealed tanks). CO_2 is injected into compartment 3 and 4 (see also Figure 4 in the Appendix). The pressure modelling of compartment 4 gave a very high model-monitoring conformity. The pressure modelling of compartment 3 resulted in a good model-monitoring conformity, but one well (K12-B6) had some issues. The modelled and measured pressures matched during the injection phase, but during shut-ins the measured pressures remained higher than expected. The observed irregularity in the BHP (bottom hole pressure), can be used to test the practicability of the workflow for decision making in site abandonment.

4.1 Application of the traffic light system to K12-B

The evaluation starts with Node 1 of the traffic light system (Figure 3). The status is assumed as green. The generic T-criteria 1 and 2 (Table 4) are assumed to be fulfilled.

Node 1 > Node 2:

The main target in verifying the storage concept is pressure modelling and monitoring, in particular the bottom hole pressure (BHP). For compartment no 3 it was observed that the

measured pressure during shut-ins is about 30 to 40 bars higher than the simulated pressures predicted. This deviation is off tolerance and thus it is a situation which has to be evaluated by the traffic light system.

Several technical criteria were defined, which connect specific modelling and monitoring requirements:

- *T3 Duration of the time interval to check for MMO*

Because the available models primarily served a scientific purpose, no assessment was made of the required interval duration for assessing MMO. The interval for updating the reservoir model was approximately one year. The parameters which form the basis of the model are measured much more frequently (Table 5).

Table 5. Frequencies of model updates and measurements applied at the K12-B site

Type of model	Type of parameter	Frequency model update/measurement
Reservoir model		Yearly
	Well head measurements (pressures, temperatures and flow)	Hourly / Daily
	Down hole measurements (pressures, temperatures)	Once every couple of years (but preferably on a yearly basis)
	Tracer concentration measurements (hardly relevant for the post operational phase)	Dependent on the situation
	Gas composition measurements (hardly relevant for the post operational phase)	Dependent on the situation
Well model / Well Integrity	Drilling Report analysis Well integrity logs	Initial well integrity analysis before the injection; Every couple of years; Drilling Report analysis for K12-B6 for the liner and 9 5/8 casing crossing reservoir and cap rock; Well integrity log analysis for liner for B6
	Wall thickness	Yearly to every couple of years
	Annulus pressures, if available	Weekly/monthly

- *T4 Relative amount of tolerable MMO*

Due to the experimental status of the K12-B CO_2 injection pilot and the relatively small quantities of CO_2 injected, no exact *allowable* deviations from the expected/predicted values have been established. The current situation for K12-B is shown in Table 6.

Table 6. Approaches for tolerable MMOs for the K12-B site

Type of model	Type of parameter	Relative tolerable MMO
Reservoir model	Well head measurements (pressures, temperatures and flow)	GD3 states < 5%
	Down hole measurements (pressures, temperatures)	GD3 states < 5%; Needs to be determined by experts
	Tracer concentration measurements (not relevant for the post operational phase)	Needs to be determined by experts
	Gas composition measurements (not relevant for the post operational phase)	Needs to be determined by experts
Well model / Well Integrity	Drilling Report analysis, Well integrity log analysis	Integrity of the well barriers shall not be compromised
	Wall thickness	Minimum thickness depends on the casing configuration; Integrity of the well barriers shall not be compromised
	Annular pressures	If observed, monitoring and (before closure at the latest) mitigation actions have to be initiated

- *T5 Accuracy/Precision of monitoring techniques applied*

In general the uncertainties in the measurements are small relative to the model uncertainties. The accuracy of the pressure monitoring is considered to be high (T5) and sufficient for the verification with the modelling results.

- *T6 Accuracy/Precision of model(s) applied*

It is very hard to express the accuracy of the reservoir model as there are multiple factors/parameters to be taken into account. Where for a certain reservoir model the shut-in pressures might be accurately simulated, the flowing bottom hole pressures might fit poorly or vice versa. What does that say about the accuracy of the model? That probably depends on what the purpose of the model is.

The model is performing well for ‘tank’-like reservoirs like compartment 4 of the K12-B gas reservoir (T6). Apparently the model is not suitable for simulation of the relatively high shut-in BHP in compartment 3 of the K12-B gas reservoir. The observed MMO in BHP during shut-in phases is about -30%. An additional analytical model simulating the pressure effect of the water column enabled clarification of the pressure effect of water influx into well K12-B6.

Node 2 > Node 3:

From the considerations in Node 2, it was decided that the MMO is off tolerance (Status: orange). As a result of further analysis it was decided that the observed pressure deviation is a result of the water influx from the lower to the upper reservoir and is not affecting the containment of CO_2.

- *T7 Does a gathered MMO refer to site irregularity or is model recalibration required?*

If a plausible model adjustment/recalibration can reduce an MMO to acceptable values and the model still complies to the boundary conditions set, the initial MMO should not refer to a site irregularity. The conclusion is that the observed pressure anomaly in compartment 3 does not represent a significant irregularity and it is sufficient to adjust the model.

Node 3 > Node 12:

The reservoir model was expanded with an analytical model describing the pressure effect of the water column in the well. Developing a new model with an integrated flux term for the fluids ascending from the lower reservoir is suggested.

Node 12 > Node 11:

The new concept adequately describes the pressure evolution in well K12-B6.

Node 11 > Node 2 > Node 1:

The new model conforms with the observed pressures in well K12-B6, which brings the system back to regular site behaviour (Status: green).

5. Conclusion

The criteria to be applied for the transfer of responsibility of the storage site from an operator to a Competent Authority demanded by the EC Storage Directive (Directive 2009/31 EC) have been connected to subsets of criteria, which are applicable at an operational level.

The primary subset is based on criteria extracted from the risk management plan developed within the scope of CO_2CARE (CO_2CARE, 2013a), termed “R-type” criteria. All R-type criteria, which are connected to modelled and monitored data, require additional risk management treatment in order to be able to evaluate irregularities in the accordance of monitoring and modelling data.

For this purpose a traffic light system has been set up, resulting in an additional set of criteria, termed technical or “T-type” criteria.

A draft traffic light system developed earlier in CO_2CARE has been tested in practice on the CO_2 storage pilot K12-B site. This resulted in a number of recommended changes of the initial traffic light system, which have been implemented in the final version presented in this report.

The practicability of the proposed traffic light workflow could be demonstrated and it is shown how the traffic light system can support the decision making in CO_2 storage site responsibility transfer and abandonment by presenting an example of how to deal with an unpredicted behaviour or irregularity of the storage site.

The approach to define criteria leading to the transfer of responsibility for the site revealed that, although based upon a generic framework, the definition of such criteria is highly site dependent. In particular, the definition of tolerable model-monitoring deviations and required accuracies/precisions of models and monitoring techniques is ambiguous and requires thorough considerations by the operator of the site and the Competent Authority.

Although the traffic light system was designed for treating irregularities in the final stages of the storage lifetime it is well applicable to the treatment of irregularities in all stages of a storage project.

6. References

CO_2CARE (2011): D4.11 Draft and updated plan for risk management supporting site abandonment.

CO_2CARE (2012): Tool for assessing model probabilities by comparing measurement and computations, CO_2CARE report, Deliverable D4.4.

CO_2CARE (2013a): Deliverable D4.12 “Risk management plan supporting site abandonment”

CO_2CARE (2013b): Deliverable D4.6 “Plan and risk management for abandonment of the K12-B site”

EC (2009): Directive 2009/31/EC of the European Parliament and the Council of 23 April 2009 on the geological storage of carbon dioxide. Official Journal of the European Union L140, 114-134.

EC (2011): Implementation of Directive 2009/31/EC on the Geological Storage of Carbon Dioxide, Guidance Document 3, Criteria for Transfer of Responsibility to the Competent Authority, Draft document for consultation. http://www.zeroemissionsplatform.eu/index.php?option=com_downloads&id=775

Kampmeinert, D.J. (2003): Winningsplan K12-B. Gaz de France Res/030072/HG/as

Nepveu, M., Kroon, I.C., Fokker, P. (2010): Hoisting a Red Flag: An Early Warning System for Exceeding Subsidence Limits. Math Geosci, (42), 187–198.

Vanderweijer, V.P. & Flach, T. (2010): Evidence for long-term integrity of the K12-B storage site. CO_2ReMoVe, Deliverable D2.8.2, Contract n° SES6 518350.

APPENDIX

Introduction to the K12-B site

As mentioned above the EC Directive for Geological Storage of CO2 (EC, 2009) does not apply to K12-B because the storage operation is performed under the gas production licence.

K12-B will be used in the context of CO_2CARE to mimic the procedure of abandon a CO_2 storage field according to the requirements and regulations for a CO_2 storage field. This is a purely synthetic exercise. It is expected that K12-B will be abandoned according to the requirements of a conventional Dutch offshore gas field and in accordance with applicable legislation in power.

(Modified from Vandeweijer and Flach, 2010). The K12-B gas field is located in the Dutch sector of the North Sea. The top of the reservoir lies approximately 3800 meters below sea level, and the ambient temperature of the reservoir is over 127 ºC. The K12-B gas field has been producing natural gas from 1987 onwards and is currently operated by GDF SUEZ E&P Nederland B.V. The natural gas has an initial CO_2 content of 13%, which is relatively high. Since the start of the gas production the CO_2 component has been separated from the natural gas stream on-site and since 2004 part of the separated CO_2 is re-injected into the gas field.

Geological research indicates that the K12-B field consists of a number of tilted fault blocks (Figure 4) which are not or barely in pressure communication with one another.

The reservoir section of the K12-B field consists of Rotliegend sandstones. In the K12 area, the Upper Rotliegend Group consists of the following stratigraphic units from top to bottom: Ten Boer Claystone, Upper Slochteren Member, Ameland Claystone, Lower Slochteren Member (Figure 5).

The top and side seal of the K12-B field are provided by rock salt of the Zechstein Group. It attains a thickness directly above the reservoir of some 500 m. An additional side seal with a thickness of some 600 m along the main bounding fault is also provided by the Zechstein. There are no faults that cross the entire Zechstein interval. Above the Zechstein the Triassic, Jurassic, Lower and Upper Cretaceous, and Tertiary are present (Figure 5).

The CO_2 is being injected in the Upper Slochteren Member, Rotliegend, of Permian age. Sedimentary heterogeneities include a complex interfingering of high-perm (300-500 mD) aeolian facies, low-perm fluvial facies (5-30 mD), and mud-flat facies; the latter act as vertical permeability barriers. It is most likely that the several meters thick aeolian streaks, which form about 11% of the gross rock volume, will act as conduits for the CO_2. The lateral extent of individual streaks is estimated to be no more than a few hundred metres. Shale streaks comprise 16% of the volume and fall into two categories: A minority has a field-wide extent, while most of the shale streaks cannot be correlated across more than two or so wells, corresponding to a lateral extent of a few hundred meters.

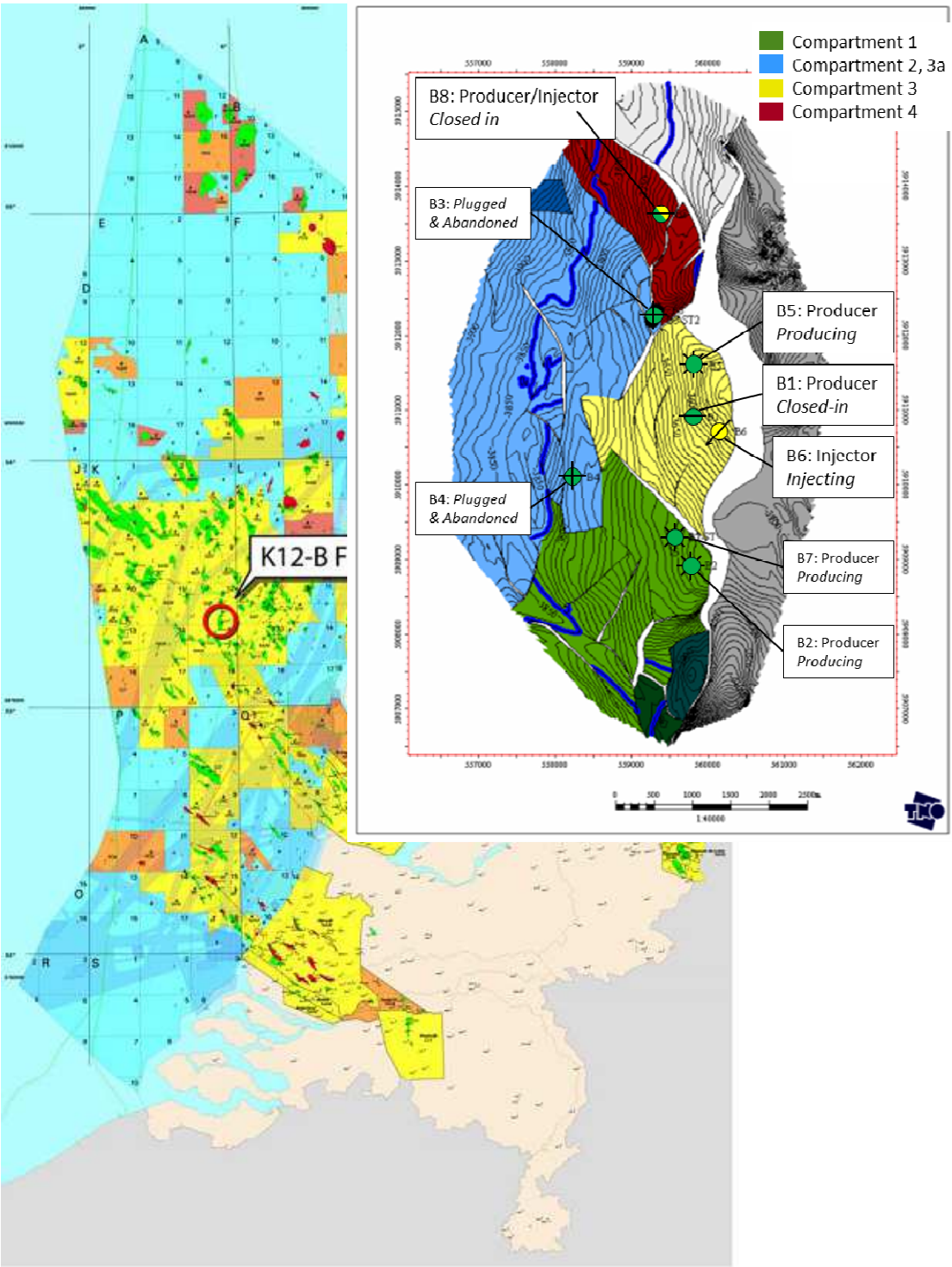

Figure 4. Location of the K12-B gas field offshore the Netherlands. Inset: structure map of the K12-B field and its compartments (Kampmeinert, 2003).

Diagenesis is considered to be the main controlling factor for fluid flow in the reservoir compartment. Its influence is exhibited in three different ways:

1. Vertical permeability is severely hampered by diagenesis. Several phases of diagenetic processes resulted in the formation of authigenic illite, kaolinite, and carbonate cements, which at places effectively block vertical flow through the reservoir. These diagenetic zones seem to be confined to the shale streaks.
2. Most fault zones are completely cemented, as testified by well K12-B03 which penetrates a fault, and by the virgin pressures encountered in undrained fault compartments.
3. Permeability and porosity are much lower in the water-bearing zone below the gas which can be attributed to the presence of diagenetic cement.

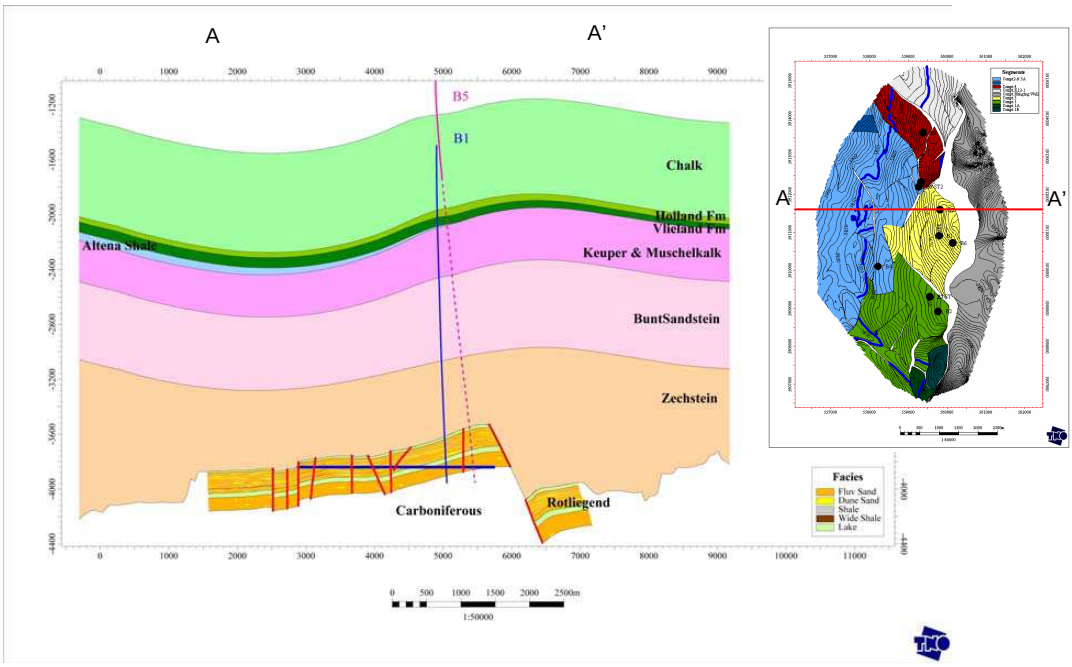

Figure 5: NE-SW cross-sections through the summit of the K12-B reservoir showing structural features, facies model, Rotliegend reservoir and overburden stratigraphy (Tertiary omitted)