ANNEX 16.2: CO2 Monitoring Plan and Corrective Measures Plan

Environmental Impact Assessment (EIA) of the Project: CO2 Storage Unit in Prinos

Έργο	Μονάδα Αποθήκευσης CO_2 στον Πρίνο		
STUDY STAGE	Draft Stakeholder Participation in the context of the Environmental Impact Assessment (EIA)		
CODE STUDY	CCP - 2902		
DATE	25.11.2024		
VERSION	v.01		
REVISION	v.01		
ENV. CONSULTANT	LDK CONSULTANTS A.E. – WSP SA		
PROJECT ORGANISER	ENEARTH GREECE		
ELABORATION	LDK – WSP study group		
CONTROL	Kostis Nikolopoulos, LDK Project Manager Anna Borroni, WSP Project Manager		
APPROVAL	Kostis Nikolopoulos Project Manager	LDK CONSULTANTS A.E. ΠΑΡΟΔΟΣ ΘΗΒΑΪΔΟΣ 21 - ΚΗΦΙΣΙΑ - Τ.Κ. 145 64 ΤΗΛ. 210 8196700 Α.Φ.Μ. 094061957 - ΔΟΥ: Φ.Α.Ε. ΑΘΗΝΩΝ ΑΡ. ΓΕΜΗ : 324501000	
APPROVAL	Vasilis Tsetoglou Director of Health, Safety and Environment		
PROJECT ORGANIZATION REPRESENTATIVE	Katerina Sardi, Managing Director – Country Manager	ENEARTH GREECE ΜΟΝΟΠΡΟΣΩΠΗ Α.Ε ΛΕΩΦ.ΚΗΦΙΣΙΑΣ 32 - ΜΑΡΟΥΣΙ Τ.Κ. 151 25 ΤΗΛ. 210 81 74 200 – FAX. 210 81 74299 ΑΦΜ: 802522310 – ΔΟΥ ΚΕΦΟΔΕ ΑΤΤΙΚΗΣ	

LDK CONSULTANTS

THE PAGE HAS BEEN INTENTIONALLY LEFT BLANK

CONTENTS

TABLES

FIGURES

1 CO_2 MONITORING PLAN AND CORRECTIVE MEASURES PLAN

1.1 CO_2 MONITORING PLAN

Energean will implement a Monitoring Plan of Paragraph 2 of Article 14 of Joint Ministerial Decision 48416/2037/E.103/2011), which is prepared in accordance with the requirements of Annex II of the above Joint Ministerial Decision. Monitoring of the injection wells of the storage complex (including, whenever possible, the CO2 plume), and, where applicable, the surrounding environment, will be carried out, with the aim of:

- comparing the actual and modelled behaviour of CO2 and formation water at the storage site,
- detecting significant anomalies,
- detecting CO2 migration,
- detecting CO2 leakage,
- detecting significant negative impacts on the surrounding environment, including in particular on drinking water, human populations or users of the surrounding biosphere,
- assessing the effectiveness of any corrective measures taken pursuant to Article 17 of Joint Ministerial Decision 48416/2037/E.103/2011.

The Monitoring Plan will assess the short-term and long-term safety and integrity of the storage complex (including whether the stored CO2 will remain fully and permanently isolated).

The Monitoring Plan covers the main stages of the Project, including basic monitoring during operation and after closure. For each phase, the following is specified:

- the parameters monitored,
- the monitoring technology used based on best available practices, and the justification for the choice of technology,
- the monitoring locations and spatial sampling logic,
- the frequency of application and the temporal sampling logic.

1.1.1 Monitoring Parameters

The monitoring plan will include continuous or periodic monitoring of the following parameters:

1. Fugitive CO2 emissions at the injection equipment,
2. Volumetric CO2 flow at the injection wellheads,
3. Pressure and temperature of CO2 at the injection wellheads (to determine mass flow),
4. Chemical analysis of the injected material,
5. Reservoir temperature and pressure (to determine the phase behavior and state of CO2).

1.1.2 Basic plan for monitoring potential CO2 leakage routes in Prinos

The Core Monitoring Plan is proposed to focus on identified leakage pathways, particularly those classified as the most hazardous. Therefore, the monitoring plan should focus on identifying any potential migration outside the injection targets along the identified leakage pathways.

1.1.2.1 Monitoring technologies

To address the potential CO2 leakage pathways identified following a structured Subsurface Risk Mitigation Assessment, as well as to address the overall risks of loss of CO2 containment through existing and future drilling, various alternative technologies are being considered.

The following options are being considered and used for monitoring technologies:

- technologies that can detect the presence, location and migration pathways of CO2 below and at the surface.
- technologies that provide information on the volume-pressure behavior and surface/vertical saturation distribution of the CO2 plume to more accurately fit the digital 3D simulation to the 3D geological models of the storage formation.
- technologies that can provide a broad surface spectrum to obtain information on any previously undetected potential leakage pathways across the surface dimensions of the complete storage complex and beyond, in the event of significant anomalies or migration of CO2 outside the storage complex.
- These technologies include instruments located near or on the seabed, such as inclinometers and active seismic instruments, as well as instruments included in the well monitoring plan for ongoing monitoring and evaluation.

It is also important to emphasize that the proposed monitoring strategy has the capacity not only to address the risks of loss of CO2 containment, but also other types of Project risks related to storage capacity, injection potential, potential induced seismicity and management design.

Table 17-1 presents the proposed Monitoring, Measurement, and Verification (MMV) plan for potential CO2 leakage pathways at Prinos. It includes several technologies recommended for both the Baseline and Contingency plans (Section 17.2.2). In addition, the plan describes a response strategy and potential corrective actions.

Table 17-2 highlights which potential CO2 leakage pathways are covered by specific techniques. Potential leakage pathways associated with the subsurface are labeled #V1 to #V5 for potential vertical Leakage Pathways, and #L1 to #L3 for potential horizontal Leakage Pathways outside the designated Prinos storage complex.

The technologies indicated in red in Table 17.2 are applied to the subsurface leakage paths that require greater attention, namely #L1, but also #L2 and #V1, #V2 and #V3, as the possibility of leakage in these paths is enhanced due to the age of the old boreholes in Prinos and North Prinos.

1.1.2.2 Baseline data acquisition (before CO2 injection)

The following monitoring methods are proposed:

- Baseline logging using 3D cable-borne seismic or seabed loggers (OBN): Coverage will be defined once the final design is complete.
- Micro-seismicity database logging & 3D vertical seismic profile (3D DAS-VSP):
- The fiber optic (FO) cable that will be installed in the injection wells and possible monitoring wells can also be used as a seismic (acoustic) signal sensor, allowing the "listening" of the surrounding micro-seismicity, as well as obtaining a seismic image of the subsurface, i.e. the 3D-DAS-VSP (3D Vertical Seismic Profile).
- It should be assessed whether the use of FO cables in the wells is sufficient and whether receivers or stations on nearby platforms are sufficient to monitor any induced seismicity that could be associated with the injection operations. A feasibility study is also required to determine the extent of seismic recording.
- Inclinometers: Micro-deformation is one of the most important technologies for monitoring injection and its effect on the uplift of overlying strata. A series of inclinometers should be installed prior to injection to ensure the detection of any deformation associated with the injection operations.
- Baseline logging using electrical mapping: This should include a baseline of pulsed neutron measurements, sigma/neutron pulse measurements, cement and casing evaluation, and reservoir fluid sampling.
- Environmental and subsea surveys: It is recommended that an environmental data base be obtained. These surveys include sampling of bottom sediments, flora and fauna, and multibeam echo sounding (MEBS) and/or side scan sonar (SSS) for bottom imaging. In addition, baselines of bottom, flora and fauna sampling should be established for geochemical characterization and monitoring.
- Fluid and physical tracer sampling: To address any potential follow-up issues during or after injection operations, it is recommended to take at least a baseline sample of the reservoir fluids and CO2 to be injected.

1.1.2.3 Data acquisition during CO2 injection

The following monitoring methods are proposed:

- Through-bore monitoring methods: pressure and temperature gauges in the deepest permeable formation outside the storage complex (above the brown marker zone, in the post-Messian sequence), as well as a Fiber Optic (FO) cable.
- The Pressure and Temperature Gauges and the Fiber Optic (FO) cable are recommended to be installed in the deepest permeable unit within the secondary CO2 containment system (Messian evaporative sequence). This can be achieved by drilling new monitoring wells, the location of which has not yet been determined, or by installing suitable gauges behind the protective casing of the injection wells (LinX system), or by reusing any old wells.

- Pressure/Temperature meters at the depth of the CO2 injection, as well as the use of a Fiber Optic cable, are also proposed to be installed in the injection wells.
- The presence of a Fiber Optic cable can be applied for the purposes of monitoring the reservoir and the distribution of the injection wells, by measuring the acoustic signal (Distributed Acoustic Detection - DAS) and/or the Temperature signal (Distributed Temperature Detection - DTS) associated with the flow of the reservoir CO2. Also, any possible leakage in the A-annulus of the well or in the overlying rock can be detected.
- 3D DAS-VSP: Assuming 20 years of intrusion operations, it is proposed to acquire 3D DAS-VSP surveys at years 2, 5, 8, 10, 15 and 20. The last survey will be taken immediately after the completion of intrusion operations to support platform decommissioning and possible early handover of the site. A different frequency may be set depending on the actual intrusion operations and the results of the initial monitoring, as well as the availability of any other less intrusive and/or effective technology.
- Inclinometers: Inclinometers can monitor ground deformation during intrusion. During the period of intrusion the ground level can be pushed upwards and inclinometers attached to the seabed can monitor these anomalies. To collect data from inclinometers attached to the seabed, it is necessary to provide a vessel that acquires the data once every desired period of time. It is also possible to acquire the data with unmanned underwater drones. Underwater inclinometers are battery operated and require replacement every 2-3 years. Having an array of inclinometers allows for simultaneous, low-cost monitoring of other tasks, such as recording hydraulic fracturing repairs.

Προτείνονται οι ακόλουθες μέθοδοι παρακολούθησης:

1.1.2.4 Environmental and Underwater Research

Assuming injection operations for 20 years, it is proposed to repeat the environmental surveys in years 2, 5, 8, 10, 15 and 20. The last record will be acquired immediately after the completion of injection operations.

As part of the seabed monitoring strategy, ROVs and other environmental photographic techniques can be focused on the platform and drillings. These less intrusive techniques can minimize the need for regular sampling of seabed flora / fauna / sediments.

In addition, a different frequency can be set depending on the actual injection operations and the results of monitoring in the early stages of the Project.

In any case, the CO2 monitoring program will be carried out in accordance with the general monitoring program in Section 13.2 of this EIA.

1.1.3 Proposed CO2 Monitoring Plan

Table 17-1 presents the proposed Monitoring, Measurement, and Verification (MMV) plan for potential CO2 leakage pathways at Prinos. It includes several technologies recommended for both the Baseline and Contingency plans (Section 17.2.2). In addition, the Monitoring plan describes a response strategy and potential corrective actions.

Table 17-2 highlights which potential CO2 leakage pathways are covered by specific techniques. Potential leakage pathways associated with the subsurface are labeled #V1 to #V5 for potential vertical Leakage Pathways, and #L1 to #L3 for potential horizontal Leakage Pathways outside the designated Prinos storage complex.

Figure 17-1 gives an indication of the monitoring techniques that are planned to be implemented at each stage during the evolution of the CO2 Storage Project.

Table 1-1: Overview of the proposed monitoring plan

Monitoring options			Pre-injection Characterisation / Base line	Conformance	Containment	
					Well related	Geological
Characterization / Base Monitoring Plan	Surface	2D / 2DHR seismic lines (to fill any gaps from DAS-VSP)	Yes/No			
		Surface Passive seismic – Microseismicity	Yes			
		Environmental/seabed surveys/sampling	Yes			
		Tiltmeters	Yes			
	Injection/Monitor Wells	3D DAS-VSP	Yes			
		Annuli & downhole P&T gauges	No			
		Fibre Optics (DTS/DAS)	No			
		Behind casing P&T gauges (LinX)	No			
		P&T gauges in Monitor wells (Storage units only)	No			
		Fibre Optics (DTS/DAS) in Monitor wells	No			
		Overburden (Out-of-Zone) P&T gauges exclusively in Monitor wells	No			
		Sigma/Neutron logging	Yes			
		Pulsed Neutron logging (IntelliSat™)	Yes			
Triggered or Contingency Plan	Surface	OBN 3D survey	Yes			
		Streamer 3D survey	Yes			
		Seawater / Bubble stream chemistry + AUV (Sniffer)	Yes			
		Multi Beam Echo Sounder	Yes			
		Side Scan Sonar	Yes			
		Gas-flux spectroscopy	Yes			
	Injection/Monitor Wells	Cement Evaluation Casing Integrity (CBL/CAST logging)	Yes			
		Passive seismic – Microseismicity	Yes			
		Fluid sampling / Natural tracers in Monitor wells	Yes			
Response Plan (After Triggered Plan)		Manage injection	NA			
		Stop injection some/all wells	NA			
		Drill Pressure relief well	NA			
		Drill CO2 drainage well	NA			
Other options	Surface	Traditional 3D/3C VSP	Yes			
		2D/3D PRM systems				
		Gravity surveys	Yes			
		CSEM	Yes			
		Pingers / Chirps	Yes			
	Injection/Monitor	Dipole EM / X-well				
		Artificial tracers	Yes			

Table 1-2: Proposed Monitoring Plan and leakage paths[1]

Monitoring options			CONTAINMENT Geological Leak-paths		
			Across Caprock (V5)	Along faults (V1, V2, V3, V4)	Laterally outside Storage complex (L1, L2, L3)
Characterization / Base Monitoring Plan	Surface	2D / 2DHR seismic lines (to fill any gaps from DAS-VSP)			
		Surface Passive seismic – Microseismicity			
		Environmental/seabed surveys/sampling			
		Tiltmeters			
	Injection/Monitor Wells	3D DAS-VSP			
		Annuli & downhole P&T gauges			
		Fibre Optics (DTS/DAS)			
		Behind casing P&T gauges (LinX)			
		P&T gauges in Monitor wells (Storage units only)			
		Fibre Optics (DTS/DAS) in Monitor wells			
		Overburden (Out-of-Zone) P&T gauges exclusively in Monitor wells			
		Sigma/Neutron logging			
		Pulsed Neutron logging (IntelliSat™)			
Triggered or Contingency Plan	Surface	OBN 3D survey			
		Streamer 3D survey			
		Seawater / Bubble stream chemistry + AUV (Sniffer)			
		Multi Beam Echo Sounder			
		Side Scan Sonar			
		Gas-flux spectroscopy			
	Injection/Monitor Wells	Cement Evaluation Casing Integrity (CBL/CAST logging)			
		Wells Passive seismic – Microseismicity			
		Fluid sampling / Natural tracers in Monitor wells			
Response Plan (After Triggered Plan)		Manage injection			
		Stop injection some/all wells			
		Drill Pressure relief well			
		Drill CO2 drainage well			
Other options	Surface	Traditional 3D/3C VSP			
		2D/3D PRM systems			
		Gravity surveys			
		CSEM			
		Pingers / Chirps			
	Injection/Monitor Wells	Dipole EM / X-well			
		Artificial tracers			

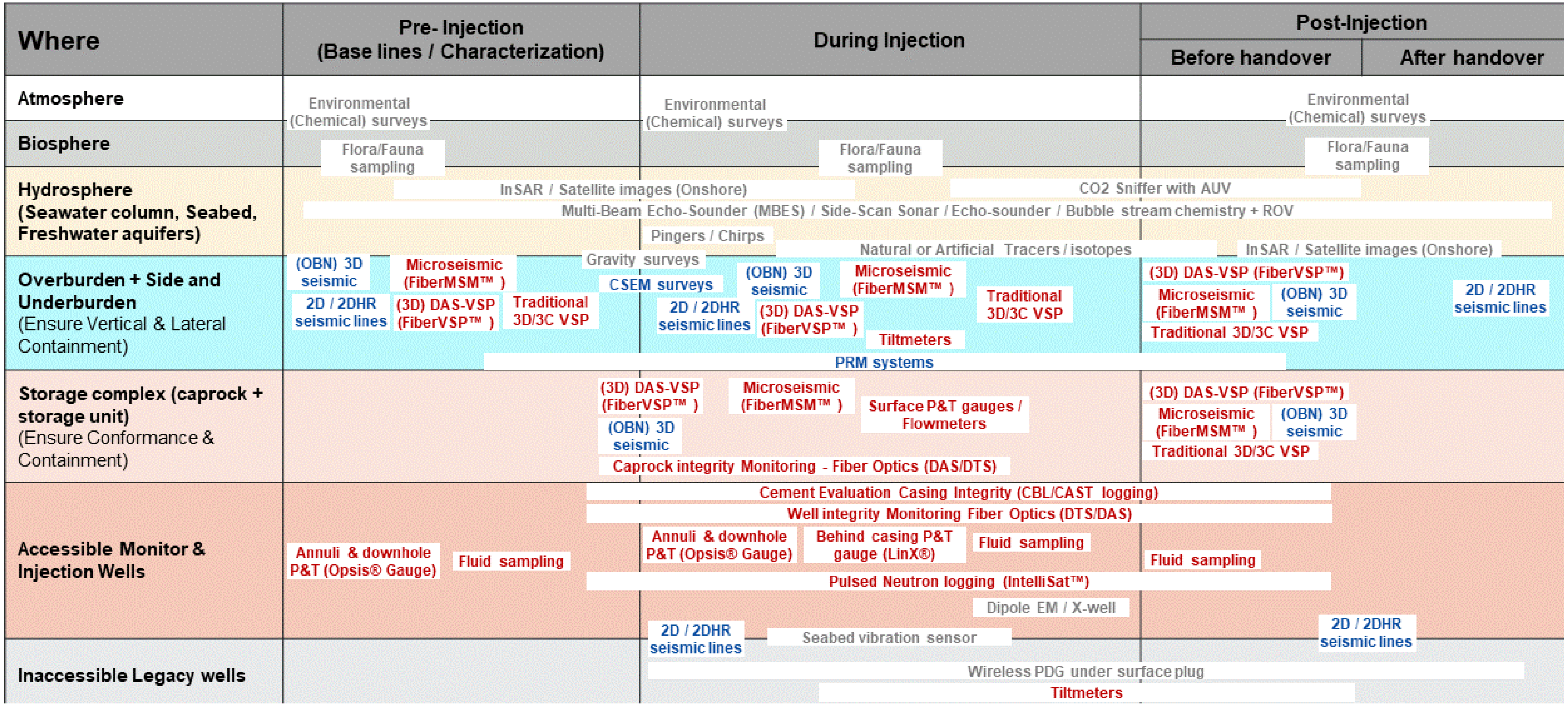

Figure 1-1: Monitoring techniques throughout the duration of the CO2 Storage Project

1.1.4 Detection and Monitoring of Leaks in CO2 Pipelines

A comprehensive approach to detecting and monitoring leaks in CO2 pipelines is achieved through a combination of methods. Monitoring for leak prevention is vital to both ensuring safe operating conditions for personnel and equipment, and to avoid operational delays and increased costs due to product loss.

The most common way to detect leaks is to monitor flow rates, pressures and temperatures at various points in the pipeline. In the event of a compressed gas leak, the sensor will register a sudden drop in pressure at the point, which will be accompanied by a possible drop in temperature. To prevent and monitor this during normal operation, pressure sensors should be installed at the inlet and outlet of the pipeline. Thermometers can also be used to continuously monitor the temperature at the inlet and outlet of the pipeline.

Chemical sensors (CO2 sensors) can be installed on land and offshore facilities to detect elevated CO2 concentrations in the air, indicating a leak somewhere along the pipeline. At the current stage of development of the CO2 capture and storage sector worldwide, the industrial application of CO2 sensors is not widespread. However, the limited number of industrial applications for CO2 detection use the Non-Dispersive InfraRed (NDIR) sensor technique, which is currently the most common and effective method for measuring carbon dioxide levels. Part of the monitoring of CO2 pipelines will be to monitor the composition of the CO2 that will end up in the injection wells. Sampling can be carried out prior to injection to ensure that the CO2 flow is within specifications from the entry point to the injection point.

1.1.5 Updating the Plan

The Plan will be updated in accordance with the requirements of Annex II of JMD 48416/2037/E.103/2011, and in any case every five years to take into account changes in the estimated risk of leakage, changes in the estimated risks to the environment and health, new scientific knowledge and improvements in the best available technology. The updated plans will be submitted to the competent authority for approval.

The data collected from the monitoring will be synthesized and interpreted. The observed results will be compared with the predicted behavior in the dynamic simulation of the three-dimensional pressure and volume and the saturation behavior.

In cases where a significant deviation is observed between the observed and predicted behavior, the three-dimensional model is recalibrated to reflect the observed behavior. The recalibration will be based on the data observations from the monitoring plan and, whenever necessary, additional data will be added to provide confidence in the recalibration assumptions.

Phases 2 (development of the 3D static geological model) and 3 (Characterization of the storage dynamic behavior, sensitivity characterization, risk assessment) of Annex I to JMD 48416/2037/E.103/2011 are repeated using the recalibrated 3D model(s) in order to generate new potential risk scenarios and flow rates and to update the risk assessment.

In cases where new CO2 sources, pathways and flow rates are identified, or significant deviations from previous estimates are observed after historical comparison and model recalibration, the monitoring plan will be updated accordingly.

1.1.6 Post-closure monitoring

Post-closure monitoring will be based on the information collected and modelled during the implementation of the monitoring plan and its updating. It will serve in particular to provide the information required to ensure the safety requirements of the closed storage site, in accordance with paragraph 1 of article 19 of Joint Ministerial Decision 48416/2037/E.103/2011.

Since no anomalies have been identified from the basic monitoring plan during the 20 years of injection operations, indicating any sign of loss of containment, it is proposed to include repeated environmental and subsea monitoring in the 5th year after the end of injection operations.

Additional passive seismic recordings in conjunction with active (2D) seismic lines could be included to demonstrate that CO2 has not migrated through local tight, extended covers, and along any old wells.

To provide further assurance of permanent containment of CO2 and to optimize the delivery period, an additional 3D repeat seismic recording could be included to provide full image coverage of the entire storage complex and all abandoned wells.

The operator will prepare a report documenting, based on all available evidence, that the stored CO2 will be kept fully and permanently contained. This report shall document at least the following:

- the correspondence of the actual behaviour of the injected CO2 to the modelled behaviour,
- the absence of detectable leakage,
- the evolution of the storage site towards a state of long-term stability.

The post-closure monitoring plan should be reviewed and finalised once discussions with the competent authorities have taken place.

1.2 CORRECTIVE MEASURES PLAN

According to paragraph 2 of article 17 of Joint Ministerial Decision 48416/2037/E.103/2011, in the event of leaks or significant anomalies, the operator is obliged to immediately notify the competent authority and take the necessary corrective measures, including measures related to health protection.

In the event of leaks and significant anomalies that pose a risk of leakage, the operator shall also notify the Climate Change and Air Quality Directorate of the General Directorate of Environmental Policy of the Ministry of Economic Development, which is the competent authority according to Joint Ministerial Decision 181478/965 (Government Gazette 3763/B/26.10.2017).

In the unlikely event that the baseline monitoring plan detects any anomaly that may indicate CO2 leakage outside the storage complex (loss of containment), injection will be immediately stopped to assess the situation before further corrective action is taken.

Additional testing will then be conducted to help determine the most appropriate corrective action. The proposed Contingency Monitoring Plan includes the following:

- Repeat 3D wireline seismic logging: It is proposed to evaluate scheduling at least one repeat 3D seismic logging as part of the handover criteria to demonstrate that CO2 has not moved outside the storage complex laterally or vertically.
- Repeat 2D/2DHR seismic logging: It is proposed as a targeted alternative to full 3D wireline seismic logging. The choice to acquire 2D seismic lines instead of a full 3D record should be supported by an appropriate feasibility study if very specific and local anomalies are identified from the initial monitoring.
- Micro-seismicity (Passive Seismic Monitoring): Passive monitoring has been included as part of the contingency and not the core monitoring plan under the assumption that fiber optic (FO) cables are only installed in the injection wells and there are no monitoring wells. Therefore, passive seismic recordings would be more likely to operate reliably during periods of injection outage. The possibility of including micro-seismicity detection in the core monitoring plan will be examined with an appropriate feasibility study. It will be assessed whether the use of fiber optic cables in the injection wells and possible monitoring wells is sufficient or whether other alternatives with receivers or stations on nearby platforms are required to monitor any induced seismicity that could be related to the injection operations.
- Repeat logging using electrical logs: pulsed neutron, sigma/neutron, cement casing assessment (CBL/CAST logging). In particular, if there is evidence of loss of containment in any injection or monitoring well, these techniques are useful for further investigation.
- Multi-logger and/or side-scan sonar mapping: If there is evidence of a leak in the seabed, a seabed image, including the use of multi-logger echo sounders (MBES), would show areas where any fluid may be escaping.
- Based on the results of the above checks, the corrective measures mainly concern the following:
- Management of the injection process and possible modification of operating parameters.
- Stopping injection in some or all wells.
- Drilling an auxiliary well to reduce pressure (water well).