MONACO—Monitoring Approach for Geological CO_2 Storage Sites Using a Hierarchical Observation Concept

Claudia Schütze, Karin Bräuer, Peter Dietrich, Viktoria Engnath, Michael Gisi, Gunnar Horak, Carsten Leven, Alexander Lübben, Ingo Möller, Michael Nierychlo, Stefan Schlömer, Andreas Schuck, Ulrich Serfling, Arno Simon, Thomas Streil and Uta Sauer

Abstract The reliable detection and assessment of potential CO_2 leakages from storage formations require the application of assurance monitoring tools at different spatial scales. Such tools also play an important role in helping to establish a risk assessment strategy at carbon dioxide capture and storage (CCS) facilities. Within the framework of the MONACO project ("Monitoring approach for geological CO_2 storage sites using a hierarchical observation concept"), an integrative

C. Schütze (✉) · P. Dietrich · U. Sauer
Department Monitoring and Exploration Technologies, UFZ – Helmholtz Centre for Environmental Research, Permoserstraße 15, 04318 Leipzig, Germany
e-mail: claudia.schuetze@ufz.de

K. Bräuer
Department Catchment Hydrology, UFZ – Helmholtz Centre for Environmental Research, Permoserstraße 15, 04318 Leipzig, Germany

I. Möller · S. Schlömer
Department 1.5 Resource Geochemistry, Federal Institute for Geosciences and Natural Resources (BGR), Stilleweg 2, 30655 Hannover, Germany

C. Leven · A. Lübben
Center for Applied Geoscience, University of Tübingen, Hölderlinstr. 12, 72076 Tübingen, Germany

A. Schuck · U. Serfling
GGL Geophysik und Geotechnik Leipzig GmbH, Bautzner Straße 67, 04347 Leipzig, Germany

M. Nierychlo
AXIO-NET GmbH, Osterstraße 24, 30159 Hannover, Germany

G. Horak · T. Streil
SARAD GmbH, Wiesbadener Str. 20, 01159 Dresden, Germany

M. Gisi · A. Simon
Bruker Optik GmbH, Rudolf-Plank-Str. 27, 76275 Ettlingen, Germany

V. Engnath
MapConcept Ltd., Gohliser Straße 13, 04105 Leipzig, Germany

A. Liebscher and U. Münch (eds.), *Geological Storage of CO_2 – Long Term Security Aspects*, Advanced Technologies in Earth Sciences,
DOI 10.1007/978-3-319-13930-2_2

hierarchical assurance monitoring concept was developed and validated with the aim of establishing a modular observation strategy including investigations in the shallow subsurface, at ground surface level, and in the atmosphere. Numerous methods and technologies from different disciplines (such as chemistry, hydrogeology, meteorology, and geophysics) were either combined or used complementarily to one another, with results subsequently being jointly interpreted. Patterns of atmospheric CO_2 distributions in terms of leakage detection can be observed on large scales with the help of infrared spectroscopy or micrometeorological methods, which aim to identify zones with unexpected or anomalous atmospheric CO_2 concentrations. On the meso-scale, exchange processes between ground surface level and subsurface structures need to be localized using geophysical methods and soil gas surveys. Subsequently, the resulting images and maps can be used for selecting profiles for detailed in situ soil gas and geophysical monitoring, which helps to constrain the extent of leakages and allows us to understand controlling features of the observable fluid flow patterns. The tools utilized were tested at several natural and industrial analogues with various CO_2 sources. A comprehensive validation of the opportunities and limitations of all applied method combinations is given and it shows that large spatial areas need to be consistently covered in sufficient spatial and temporal resolutions.

1 Introduction

In recent years, global concerns about greenhouse gas emissions have stimulated considerable interest in carbon capture and storage (CCS) as a climate change mitigation option which can be used to reduce man-made CO_2 emissions. This is achieved by separating and capturing CO_2 from emission sources, then injecting and storing it in the subsurface. While the public perception of CCS nowadays is rather negative, the IPCC states that the majority of CCS deployment will occur in the second half of this century (IPCC 2005). Therefore, techniques are needed to measure the amount of CO_2 stored at a specific sequestration site, to monitor the site for leakages and storage integrity over time, and to verify that the CO_2 is safely stored and not harmful to the host ecosystem (Hovorka 2008).

The IPCC also states that CO_2 storage risks are comparable to those associated with similar industrial operations, such as underground natural-gas storage (UNEP 2006). However, the greatest environmental risk associated with CCS technology is gradual leakage through undetected faults, fractures or wells, or the potential problems caused by leakages due to injection well failure or leakages up through an abandoned well. These potential leakages could negate the initial environmental benefits of capturing and storing CO_2 emissions and may have harmful effects on human health (Georgiou et al. 2007). Successful monitoring plans need to cover different areas at different scales to enable detection of any significant irregularities, or CO_2 migration paths and any leakages at the surface. The detection of atmospheric releases is especially necessary to establish an early warning system and to plan mitigating actions. Benson (2006) stated that an effective monitoring program should first of all focus on detecting whether or not emissions are occurring. Once any actual or possible emissions are detected, more detailed investigations are necessary for precise localization and quantification. Therefore, a monitoring concept combining appropriate methods is needed to gain timely information about the location of migration paths, seepages, and the CO_2 distribution in the shallow subsurface.

2 Application of a Hierarchical Monitoring Approach

There are two distinct purposes for undertaking monitoring at CO_2 storage sites: (1) to ensure conformance by tracking the pressure buildup and CO_2 inside the storage complex, thereby helping to indicate the long term security of the site ('integrity monitoring') and (2) to ensure containment by triggering timely control measures to mitigate any unexpected leakage, helping to demonstrate the current security situation, especially in the area surrounding the storage complex ('assurance monitoring') (Bourne et al. 2014). Several geochemical and geophysical (such as time lapse seismics) techniques allow for monitoring of the regional distribution of CO_2 in the storage complexes, seal integrity and the pressure evolution in response to injection. They can therefore be used to verify storage conformance and are valuable tools for integrity monitoring (IEA 2012). Assurance monitoring is used to compare pre- and post-injection properties to verify containment and the absence of any environmental effects outside the storage complex. These assurance monitoring tools must consider various monitoring zones (atmosphere, biosphere, ground surface, aquifer/vadose zone, and storage formation), their lateral variabilities and transport-relevant flow paths.

The aim of the MONACO project was to apply and validate a near-surface monitoring concept covering different scales to enable reliable detection of CO_2 migration and seepage. Our approach focuses on the development of assurance monitoring techniques—especially in the atmosphere, at surface level and in the vadose zone or the saturated zone. Applied groundwater, soil, soil gas, and atmospheric monitoring tools provide data about environmental integrity at increasing distances from the reservoir. Large-scale atmospheric monitoring methods are applied to investigate air composition to help determine unexpected CO_2 levels. Subsequently applied meso- and point-scale surface and near-surface monitoring techniques focus on structural settings in the subsurface and CO_2 interaction processes with the aim of identifying areas of risk for human beings and ecosystems.

According to Bourne et al. (2014), a successful monitoring plan complies with regulatory requirements (e.g., requirement to perform adequate pre-injection characterization and baseline monitoring), clearly defines monitoring objectives for risk assessment (risk based monitoring); selects appropriate monitoring tools for the site (site-specific monitoring); and continuously evaluates the monitoring systems (adaptive monitoring) (Bourne et al. 2014). Appropriate site monitoring requires a suitable and modular design to select the right tool, to meet the right need, at the right phase of the implementation (Fig. 1).

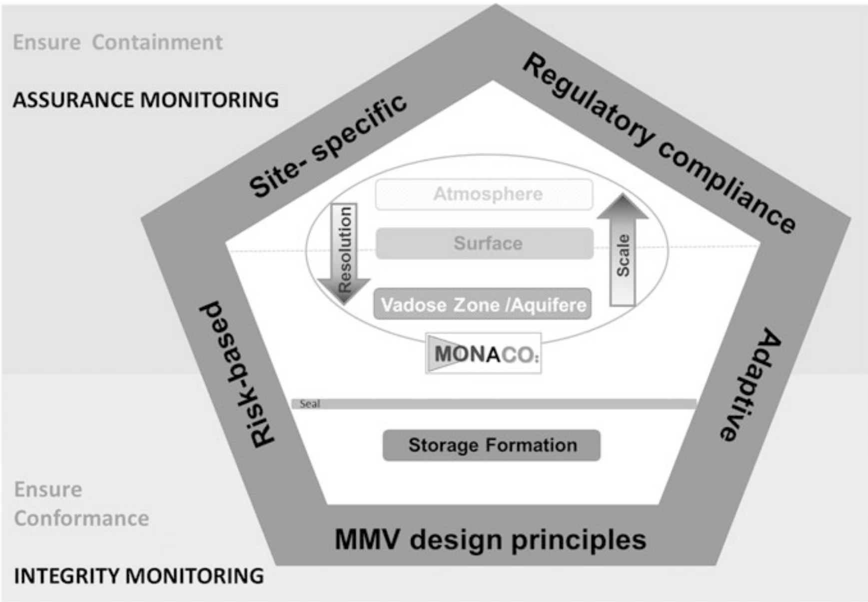

Fig. 1 Illustration of measurement, monitoring and verification (*MMV*) principles (Bourne et al. 2014) and different monitoring zones to monitor CO_2 accumulation, possible migration paths and CO_2 leakages. The project MONACO considers near-surface monitoring zones and applies monitoring methods with different resolution and applicable at different scales

Results and lessons learned from the MONACO approach were primarily obtained by applying the integrative monitoring concept including the practical field work and the necessary data processing. Field work was carried out on several test sites with normal ambient CO_2 conditions in the Altmark region (Northern Germany) and on two natural CO_2 degassing sites in the Cheb Basin (Czech Republic) and Starzach (Baden-Württemberg, Germany).

The Cheb Basin (NW Bohemia) is a CO_2 leaking natural analogue and is a promising location for directly investigating processes along preferential migration paths and verifying monitoring tools. Here, mantle-derived CO_2 is emitted from both isolated gas vents (mofettes) and from extensive diffuse degassing zones. This is caused by a structural fault as preferential pathway (Weinlich et al. 1999). The degassing vents are in some cases characterized by vegetation anomalies. Similar conditions concerning enhanced natural CO_2 exhalations were found at the Starzach site which was used for CO_2 mining in previous times.

By using a web based information system established within the MONACO project, different web map services (WMS), digital elevation models, aerial photographs, borehole information and processed monitoring data enable a comprehensive database of these sites for data interpretation.

2.1 Tools for Large-Scale Monitoring—Atmospheric Monitoring

Methods applied at large scales can provide key information about CO_2 leakage occurrences and therefore help identifying potential areas for further meso-scale investigation. The impact on the land surface and near-surface atmosphere caused by elevated CO_2 concentrations may even alter spectral reflectance or emissivity characteristics and can be detected using remote sensing techniques. Examples of such techniques include multi- and hyperspectral airborne remote sensing, as well as ground-based remote sensing infrared or laser spectroscopy (Shuler and Tang 2005).

Within a CCS site, atmospheric monitoring in the vicinity of the storage project is designed to detect and quantify emissions from potential leakage sources (e.g., permeable faults, abandoned wells). An effective atmospheric monitoring tool should satisfy the following requirements: (1) be capable of large-scale observation with sufficient spatial and temporal resolution, (2) fast application and rapid data interpretation, and (3) have sufficient sensitivity to increased atmospheric CO_2 concentrations and fluxes, triggering control mechanisms for subsequent steps. Sensors that can measure atmospheric CO_2 anomalies over open paths which are hundreds of meters long are especially useful in helping us to obtain an initial overview and first assessment of leakages, and provide the required information so that further efficient observations can be made.

2.1.1 Open-Path Fourier-Transform Infrared (OP FTIR) Spectroscopy

A promising approach for detecting elevated CO_2 concentrations along an open optical path is the measurement of absorption loss using OP FTIR spectroscopy and open-path tunable diode laser absorption spectroscopy (TDLAS) (Seto and McRae 2011; Etheridge et al. 2011; Shuler and Tang 2005; Reiche et al. 2014). These ground-based remote sensing methods are proven to be flexible long-path techniques for the characterization of larger areas, and are able to simultaneously detect various volatile atmospheric compounds relevant for environmental assessment with a single rapid measurement.

OP FTIR spectroscopy is based on the analysis of ambient (passive mode) or artificial infrared radiation (active mode) in the 700–4,000 cm^{-1} wave-number range along optical pathways (in km-range). Many greenhouse gas molecules (e.g., CO_2, H_2O, CH_4) have unique signatures (absorption or emission bands) in the spectral range under consideration. IR spectroscopy allows spatial characterization of emissions and can be applied non-invasively as an automated surveillance method in large and potentially inaccessible areas. It is proven to be a powerful technique, enabling online monitoring of fugitive emissions for industrial, environmental and health applications (Griffith et al. 2002; Harig et al. 2006; Harig and Matz 2001; EN_15483 2008).

The application of both active and passive ground-based OP FTIR spectroscopy was validated within this project as one possible method for achieving large-scale scanning of atmospheric composition, in terms of identifying areas of higher leakage vulnerability where detailed subsurface investigations (on meso- or point-scale levels) are subsequently required. Based on investigation of natural CO_2 degassing sites and analysis of industrial emissions, OP FTIR spectroscopy proved itself to be a robust and suitable monitoring method. To ensure reliable results, certain 'best practice' recommendations have to be taken into account:

- OP FTIR spectroscopy is an optical technique. Hence, unobstructed optical pathways to target zones are required. In denser industrial or urban areas, this restriction might pose a significant challenge.
- The measurements result in integral concentration values along the optical pathway. The integrative character of the measurement needs to be considered when designing monitoring schemes and when interpreting measurements with respect to the localization and quantification of emissions.
- The detection of small scale sources (e.g., point emissions) might be challenging. A dense grid of optical pathways (resulting in a large data amount) is required. However, when measuring along large distances, the ability to identify emission sources improves with increasing concentration variations. The sensitivity of the method can also be increased when considering relative temporal variability instead of absolute values.
- Site-specific influences including parameters such as principal wind direction, meteorological conditions, topographic influences, infrastructure, other artificial emission sources, and biological background need to be monitored prior to and during atmospheric monitoring.
- Atmospheric dispersion effects can have a strong impact on the detectability of CO_2 anomalies. Mixture and dilution processes in the near-surface atmosphere have to be considered and can be simulated using atmospheric dispersion models, in order to assess observed data (Flesch et al. 2005; Gal et al. 2012; Leuning et al. 2008).
- Passives open-path measurements offer the chance of achieving robust surveys in various arbitrary measurement directions, which are useful for gaining an overview. Furthermore, the large optical path lengths which can be achieved represent a key advantage when surveying large areas (several km^2). However, a passive system is not best suited for the retrieval of high-precision quantitative gas concentration data. Reasons for this include: an undefined path length and width for long pathways, complex signal behavior due to the combined emission and absorption behavior of the target gas, and problems caused by weak signals due to low temperature differences between the target gas and the background environment.
- To improve quantitative analysis in the case where weak sources are present, the application of a robust active open-path spectrometer is recommended.

> In contrast to weak passive IR-radiation emitted in the background, an active source of radiation is used, which emits a constantly high signal level leading to outstanding detection capabilities. Since the radiation path length is known, the spectrometer, by design, is sensitive to its own artificially emitted radiation only; high-precision gas concentration measurements are possible.

In our study, OP FTIR spectroscopy was evaluated and is considered to be a suitable tool for use as part of an early warning monitoring concept. A fully automated high resolution active OP FTIR spectrometer system was designed within the frame of the MONACO project, fulfilling the requirements for reliable large-scale atmospheric monitoring at CCS sites (Bruker 2014). Monitoring operation and spectral analysis can be carried out permanently and automatically with high temporal resolution. While concentration retrieval is performed in real-time, reliable interpretation of concentration values with respect to stored CO_2 leakages may require expert knowledge for each specific site. A combination with other atmospheric monitoring techniques is recommended (Fig. 2).

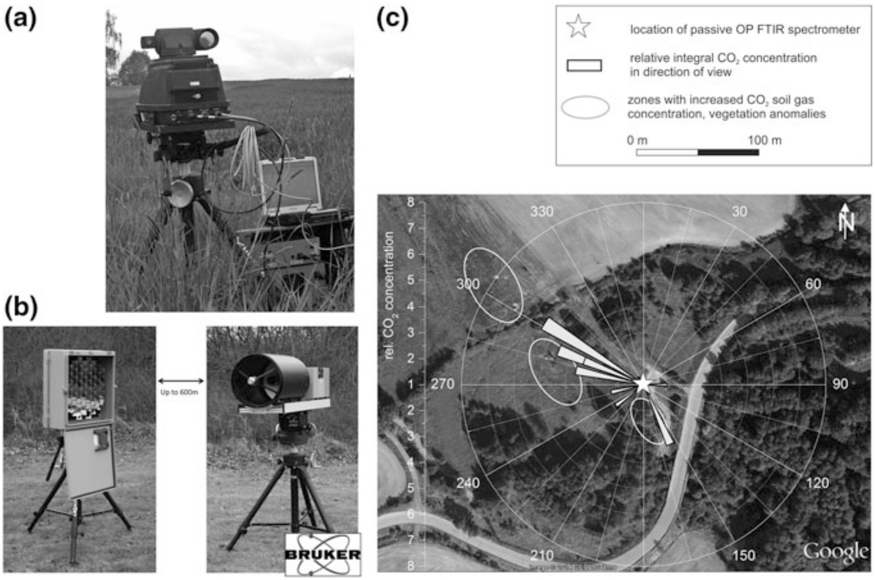

Fig. 2 Validation of OP FTIR spectroscopy to identify atmospheric CO_2 anomalies based on MONACO project results. **a** Passive monitoring equipment including passive OP FTIR spectrometer with stand-alone power supply and controlling notebook. **b** New active OP FTIR spectrometer system consisting of retroreflector (*left*) and open-path spectrometer with collimation optics (*right*) with a maximum investigation distance of 600 m. **c** Results of passive monitoring scan at a natural carbon dioxide degassing site (Czech Republic). Zones with distinctly increased atmospheric CO_2 concentration can be observed in the direction of known soil gas anomalies (modified after Schütze et al. 2013; aerial photo: Google Earth 2014)

2.1.2 Eddy Covariance Method

Looking back on more than 30 years of experience in micrometeorological and ecological studies, the eddy covariance method (EC) has often and consistently been proposed times as a potential suitable method for the monitoring of geologic CO_2 storage sites (e.g., Leuning et al. 2008). The main reason for this is the technique's capability to derive accurate gas fluxes as spatially-integrated expressions of the related exchange between the ground surface and the atmospheric boundary layer (spatial coverage range: from several hundred m^2 to a few km^2, temporal resolution: from several minutes to hours). However, previous studies have also shown that a relatively high leakage rate would be required for leakage detection via EC (Lewicki et al. 2009; Etheridge et al. 2011).

For technical and methodological comparisons, complementary near-surface CO_2 monitoring methods were deployed, along with EC equipment—namely CO_2 accumulation chambers, permanent soil CO_2 monitoring stations and air CO_2 monitoring sensors.

All aspects considered, deduction of gas exchange rates using the EC method is a complex statistical approach that is based on several restricting model assumptions that form boundary conditions for the deployment of this method (Burba 2013). Key constraints include:

- Topographical pre-conditions (necessity for a flat and homogeneous ground surface, the measurement point (location of tower) represents an upwind area)
- Technical prerequisites (instruments are able to detect minimal variations at high frequencies)
- Meteorological assumptions (fully turbulent flux, total vertical flow is negligible, steady state conditions during the flux averaging interval, air flow convergences or divergences as well as atmospheric gravity waves are negligible, air density fluctuations do not exist or can be corrected, measurements capture the boundary layer of interest).

The EC technique requires careful selection of the observation site and special precautions when undertaking technical handling of the essential instruments. Problems related to equipment setup include several sources of errors, e.g., selection of the measuring height, a possible tilting of the instruments, effects of sensor separation (namely distance between gas analyzer and anemometer), as well as distortions caused by the installations themselves. Other technical and operational demands to be considered include:

- The installed technical equipment should be constructed and set up in a way that does not disturb the existing nature of turbulence.
- The equipment must be environmentally robust and suitable for performing remote operations (e.g., low power consumption, assured power supply), while the setup and maintenance of system components (cleaning, calibration, replacements etc.) should be as easy as possible, in order to facilitate and ensure an accurate configuration of the instruments and their performance during operation.

The demands the EC method imposes regarding instrumentation, survey design and implementation, as well as data processing, are still great. However, the instrumental and data processing aspects of this approach have reached a high level of maturity. This method can be classified as being robust and reliable, even if it still benefits from technical processes concerning the instruments involved and software applications. If the boundary conditions are met, the EC technique produces accurate flux information on a medium scale with good temporal and spatial resolution. During the field experiments in our project, the instruments showed a very high availability and any system downtime was almost exclusively caused by common maintenance work or due to external factors, such as power cuts or data transfer problems. The quality of the calculated flux data depended notably on the prevailing wind conditions and, in some cases, on the influence of air moisture (relative humidity >90 %, fog, drizzle, rain). Thus, the meteorological constraint "no wind = no flux data" can unfortunately be extended to mean "weak wind = poor data quality". Nonetheless, typical data coverage in literature is in the range 65–75 % over the course of a year (Falge et al. 2001), although our experiments had slightly better temporal coverage. As a rule of thumb, the general total EC measurement error seems to be between 5 and 20 %, while Baldocchi (2003) indicates that an error of less than 7 % occurs during the day and less than 12 % at night.

Currently, there is no overall agreement on a single, standardized methodology for the EC technique, although much work towards harmonization has already been carried out by the international EC research community and its networks. Since each observation site has its own characteristics, almost every EC experiment needs to consider different parameters. Thus, the applicability of EC technique remains, to a certain extent, a site-specific monitoring approach. Use of the EC method demands expert knowledge and it is presently not a "simple, transparent technique for day-to-day monitoring practice".

If the monitoring concept focuses on CO_2 fluxes on a medium scale, the EC technique has a unique position, despite the limitations mentioned above. It has the capability to act as a methodological link between integral large-scale monitoring efforts on one hand, and small-scale approaches distributed over large areas on the other—even if some methodological developments still must be made in order to ensure a logical combination of data from different scales.

However, with regard to CO_2 storage practice, one important question arises: At what stage of storage operations is the *quantification* of CO_2 fluxes required? For all intents and purposes, extended baseline flux quantification, i.e., the identification of the natural background and its variability, is mandatory—otherwise, additional CO_2 flux caused by potential leaks cannot be quantified. Furthermore, once leakage is detected by any monitoring approach, flux quantifications are also needed in order to obtain information on how much CO_2 escapes from the storage site into the atmosphere and to identify potentially hazardous areas, initiate project remediation strategies, and to verify the success of the corrective measures. In all other phases of normal storage operations, near-surface monitoring might routinely rely on other indicators; indicators that can be more easily determined and in a more transparent way than the complex computation required for CO_2 fluxes using the EC approach.

Monitoring of CO_2 concentrations instead of fluxes would, for example, cover such an easy-to-use indicator. Strategically well-placed and fitted with elementary wind sensors, simple air CO_2 sensors can measure CO_2 concentrations straightforwardly. They provide sufficient information to ensure continuous near-surface monitoring by identifying recurring data patterns including their normal variations on one hand, but also detect potential anomalies on the other.

Both OP FTIR spectroscopy and the EC technique have been validated in our study as suitable monitoring techniques. They are near-surface atmosphere monitoring methods that work on larger scales. However, it needs to be noticed that geologic CO_2 storage is realized deep underground. It is therefore evident that it cannot cover all monitoring aspects of industrial CCS operations and must be an integral part of a comprehensive monitoring concept consisting of methods that focus on other environmental compartments or on different temporal and spatial scales.

2.2 Tools for Meso-scale Monitoring—Surface-Based Monitoring

Within our study, patterns of atmospheric CO_2 variability were observed with the help of FTIR and EC methods. In zones of increased CO_2 concentration, the source processes (man-made, natural) need to be clarified and the surface or near subsurface areas should be monitored in detail. Ground-based deformation studies, geophysical methods such as electromagnetics (EMI), electrical resistivity tomography (ERT) and self-potential (SP), soil gas concentration, flux measurements and soil moisture and temperature mapping are efficient methods for identifying near-surface structures which favor gas accumulation and migration applied in the MONACO approach. Combinations of various geophysical methods and soil-gas investigations (CO_2 concentration and flux rate) provide insights into the physical properties of sediments (e.g. resistivity variations), structural features (e.g., secondary traps) and transport processes (e.g., migration of fluids, CO_2 solution). Such an integrative approach derives information about preferential degassing pathways (e.g., Buselli and Lu 2001; Byrdina et al. 2009; Lamert et al. 2012; Pettinelli et al. 2010; Schütze et al. 2012).

2.2.1 Geophysical Methods

The application of geophysical methods is motivated by two main processes. Firstly, CO_2 (dissolved, volatile) in the pore space has an impact on physical sediment properties (e.g., electrical resistivity). Secondly, fluid movement may induce dynamic, time-dependent processes (e.g., temporal variations in geophysical parameters, generation of electro-kinetic effects). Within the MONACO project the supposed variation in geophysical parameters due to the presence of CO_2 was investigated using a combination of several geophysical methods—such as SP monitoring and mapping, EMI mapping, ERT survey and refraction seismic measurements.

The self-potential (SP) method measures a natural electrical potential field distribution at the ground surface. It is used to map distinct anomalies or to monitor temporal changes caused by dynamic processes. For field applications, it is often difficult to separate the variously superimposed sources of SP signals in the measured data induced by a combination of electrokinetic effects, electrochemical potential differences and thermoelectric coupling effects. However, the determination of streaming potentials (electrokinetic effects) could be a possible parameter to feature CO_2 migrations or could at least be an indicator for fluid transport in the subsurface (Byrdina et al. 2009; Revil et al. 1999a; Smaczny et al. 2010; Sprunt et al. 1994). It must be considered that SP anomalies are influenced by soil structure, rock variations, meteorological conditions and/or groundwater flow. Streaming potentials are sensitive to variations in hydrological parameters, which are expressed in considerable time dependence (Ernstson and Scherer 1986). Furthermore, the effect of more intense chemical reactions due to higher CO_2 concentrations in the subsurface can encourage evolution of an increased electrochemical effect on the SP values (Zlotnicki and Nishida 2003). In our measurements, the observed anomalies are potentially driven by gas flow associated with transport of a water phase within the permeable zones (Fig. 3). These effects are also observed by Byrdina et al. (2009), Revil et al. (1999b), Sauer et al. (2014), Sandig et al. (2014). Following 'best practice' recommendations, the reliable identification of influencing subsurface properties (e.g., porosity, gas or water saturations, conductivity) on the SP signal requires additional geophysical methods (e.g., ERT) and environmental data (e.g., soil gas concentration measurements) (Flechsig et al. 2008; Jardani et al. 2007).

Resistivity and electrical conductivity can act as geophysical indicators for the presence of CO_2 in pore space. Variations in resistivity depend on physical sediment properties such as conductive mineral components, porosity, clay content, water saturation, and electrolyte concentration (Flechsig et al. 2008; Knödel et al. 2007; Reynolds 2011). Recent field tests, laboratory experiments, and numerical simulation studies show that electrical resistivity is highly sensitive to the presence of CO_2 (Bergmann et al. 2012; Börner et al. 2013; Kharaka et al. 2009; Lamert et al. 2012). Gaseous CO_2 intrusion into shallow groundwater systems generally causes increased gas phase content in the soil pore space, which accordingly leads to increased bulk resistivity. However, subsequent dissolution of CO_2 in partly-groundwater saturated sediments leads to the occurrence of carbonic acid followed by generally decreased pH values and increased alkalinity. These circumstances lead to decreased bulk resistivity.

Electromagnetic induction mapping (EMI) is a non-invasive method for measuring the apparent electrical conductivity. EMI methods are considered as being a promising approach for monitoring CO_2 storage (Börner et al. 2010). Due to the small expected differences in electrical conductivity in the shallow subsurface, careful device calibration, operation, and interpretation is necessary. Our results indicate that EMI can be used as an appropriate tool for a fast and rough outline survey of the recent main geological structures. For more detailed insights, the subsequent application of geoelectrical investigations is recommended.

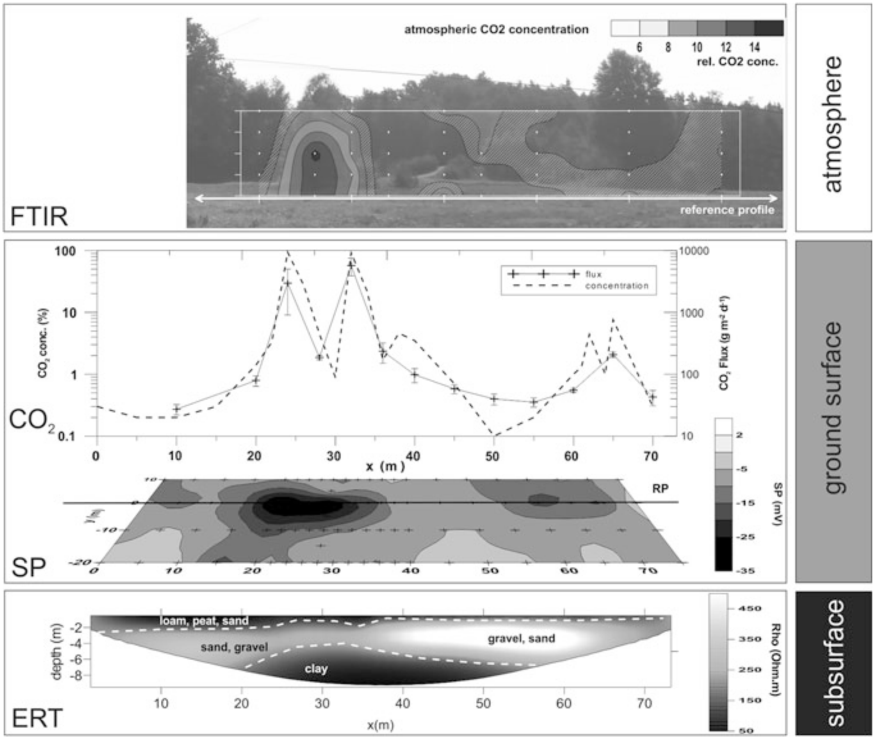

Fig. 3 Example for validation of the hierarchical approach at a natural analogue site in the Cheb basin (CZ). **Atmospheric monitoring**: Scanning passive OP FTIR spectroscopy was applied. The image shows atmospheric CO_2 concentration in relation to normal conditions. Atmospheric CO_2 concentration maximum value occurs above the main soil CO_2 degassing anomaly. **Ground surface monitoring**: Soil gas concentration distribution and soil flux measurement displays an anomaly indicating the main degassing zone. The CO_2 flux measurements using the accumulation chamber method show two distinct flux maxima above the anomaly threshold of 50 g m^{-2} d^{-1}. Soil CO_2 concentration values measured along the same soil gas profile show also two distinct concentration maxima with nearly 100 % CO_2 concentration. SP distribution at ground level: negative SP anomaly correlates with CO_2 concentration anomaly in the atmosphere and near surface. **Subsurface monitoring**: In the ERT results a distinct disturbance in the resistivity layers is obvious beneath the main degassing zone. Lithological units shown were derived from a drilling log

Electrical resistivity tomography (ERT) is a non-invasive geophysical method providing information on the subsurface resistivity pattern. Knowledge about the resistivity distribution can be applied to map shallow subsurface structures depending on the investigation depth—and is subject to electrode spacing, electrode configuration, and the resistivity distribution of the subsurface. The determination of resistivity anomalies is considered to be useful when investigating disturbances caused by variations in lithological parameters and fluid content (Flechsig et al. 2010; Schütze et al. 2012). Within the frame of the MONACO project, ERT surveys were used to reveal internal structures responsible for fluid migration or trapping in the shallow sedimentary layers. It turned out that the ERT method is a valuable tool for monitoring temporal and spatial changes in resistivity patterns due to variations in fluid transport processes. Furthermore, the analysis of resistivity anomalies is crucial when it comes to understanding the observed SP patterns (Fig. 3).

Additional shallow refraction seismic investigations were validated in the project as suitable method which helped us obtain supplementary structural information from the seismic velocity models. This method yields high resolution images concerning the structural geological setup and provides valuable data to minimize the ambiguity of geophysical models.

2.2.2 Soil Gas Surveys

Surface-based measurements of CO_2 concentration and CO_2 flux provide reliable insights in leakage processes, which can allow us to constrain the extent of potential leakages and to understand the controlling features of the observable fluid flow patterns (Schütze et al. 2012).

Reliable soil gas sampling requires a thorough sampling technique. The soil gas CO_2 concentration is measured in shallow depths (minimum sampling depth 0.5 m below ground level) and the mixture of gas samples with fresh air have to be avoided. Flux measurements are typically based on the accumulation chamber method (Chiodini et al. 1998). Both investigation techniques were validated at the test sites in the Cheb Basin and Starzach. These techniques are considered to be valuable tools for the mapping and quantifying of CO_2 seepage to the surface via preferential pathways. However, detailed soil flux and concentration investigations of larger areas are time-consuming. Changes in meteorological conditions during measurement need to be carefully considered during subsequent interpretation.

In different measuring campaigns during the project, we observed a high spatial variance of the soil gas concentration and flux on small scales with respect to location, spatial extent and amplitude. Land use, meteorological and soil moisture conditions especially influence gas migration and seepage. Therefore, the joint interpretation of soil gas measurements with geophysical data and soil moisture/temperature data is important, to gain a realistic site-specific overview for risk analysis (Fig. 3).

2.2.3 Soil Parameter Measurements

Soil temperature and soil moisture are influencing parameters on geophysical and geochemical parameters (SP, ERT, EMI and CO_2 concentration) and, as an immediate response to meteorological conditions, must be considered when carrying out data interpretation. These parameters can be mapped and monitored using standard devices such as temperature probes and soil moisture sensors based on time domain reflectometry (TDR).

Results achieved from integrative measurement taken at our test site in the Cheb basin indicate that the hierarchical monitoring approach represents a successful multidisciplinary modular concept (Sauer et al. 2013; Schütze et al. 2013). The application of OP FTIR spectroscopy in combination with soil gas surveys and ERT investigations has proven to be a valuable tool for comprehensive characterization of the atmospheric and near-surface CO_2 distribution, as well as subsurface structural features (Fig. 3).

2.2.4 Ground-Based Deformation Studies

Precise measurements of ground deformation (uplift or subsidence) can be acquired remotely using geodetic techniques e.g., radar satellites positioned above CO_2 storage sites can be used to determine the surface-level impacts of injection. It can be seen that the amount of geomechanical deformation caused as a result of CO_2 injection is likely to be a function of the volume of CO_2 injected (Verdon et al. 2013). The satellite-based Interferometric Synthetic Aperture Radar (InSAR) has proven to be successful for monitoring (to centimeter level degree of accuracy) volcanic and earthquake deformation (Zhao et al. 2012; Biggs et al. 2009) and was especially valuable when used at the In Salah CCS site (Ringrose et al. 2013; White et al. 2014).

Differential Global Navigation Satellite System (DGNSS) observations were evaluated within the project for high precision monitoring of surface deformation and movement. GNSS observations obtained from a four station reference network were post-processed using GNSS networking software. One of the reference stations was replaced by a monitoring unit consisting of a GNSS receiver and a crank unit with a mounted GNSS antenna. By using the crank unit, the height of the monitoring station were adjusted to the required level. Monthly height adjustments that were undertaken were recorded and compared with the height results obtained by GNSS post-processing analyses. Applying a special filter for the determination of coordinates for the monitoring station, the standard deviation of the time series was reduced down to 1 mm (height). Figure 4 shows the post-processing results, indicating the detectability level of the manual height changes of the crank unit.

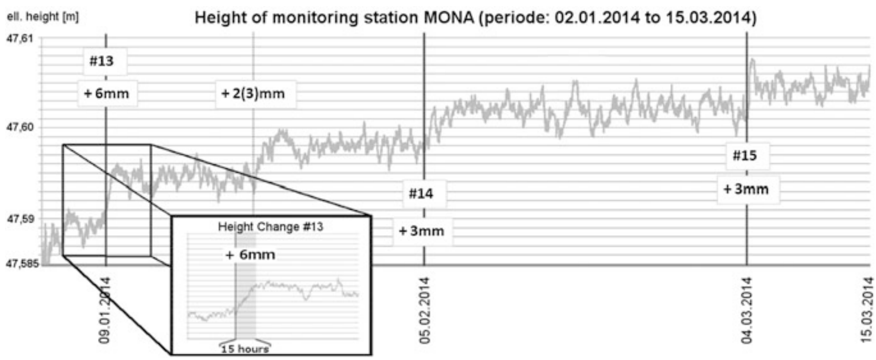

Fig. 4 Post-processing results—monitoring station MONA, The manual height changes of the crank unit are seen in the coordinate time series very clearly. Event #13 shows that the manual height change was detected in its whole magnitude after around 15 h

The results of the analyses show that when using DGNSS measurements, surface deformations of even a few millimetres can be reliably detected. Compared to other satellite based observation methods, permanent coordinate monitoring of a CCS site is possible using the GNSS approach. Deformations can be detected within a few hours.

2.3 Tools for Small-Scale Monitoring—Subsurface in Situ Monitoring

The distribution of geophysical indicators in conjunction with observed characteristic CO_2 concentration and flux patterns is useful for identifying site locations for detailed in situ monitoring. These can then be used for a further detailed determination of the lithological setting and spatial distribution of the site's permeability, while simultaneously assessing the spatial and temporal migration behavior of $CO_{2.}$ Geophysical methods (e.g., ERT and seismics), in situ installations (e.g., for CO_2 concentration and flux measurements and isotope analysis of sampling probes) are examples of monitoring tools which can be used to identify deeper geological structures responsible for gas migration and trapping, and to characterize the CO_2 source.

2.3.1 In Situ Measurements and Sampling

Direct Push technology (DP) is a minimally invasive and highly efficient tool used for in situ measurement of different physical and chemical parameters (e.g., electrical conductivity logging, hydraulic conductivity logging) and the installation of monitoring sensors into depths of up to 30 m in unconsolidated to weakly-consolidated sediments (Leven et al. 2011; Zschornack and Leven 2012; Dietrich and Leven 2006). Direct Push can also be used for retrieving soil, gas and water samples needed for chemical analysis. Soil samples provide especially valuable lithological information, which can be used to validate geophysical data.

2.3.2 In Situ Installations

At a field site in Starzach (Baden-Württemberg, Germany), a location with enhanced natural CO_2 exhalation and which was used for CO_2 mining in previous times, soil sensors designed to measure soil temperature (T), volumetric water content, and electrical conductivity (σ) were installed at two different depths (0.3 and 0.6 m below ground level). The reason for doing so was to investigate the influence of mofettes (focused CO_2 degassing) on soil parameters such as electrical conductivity and soil CO_2 concentration at different locations with characteristic low, intermediate, and high soil CO_2 concentrations.

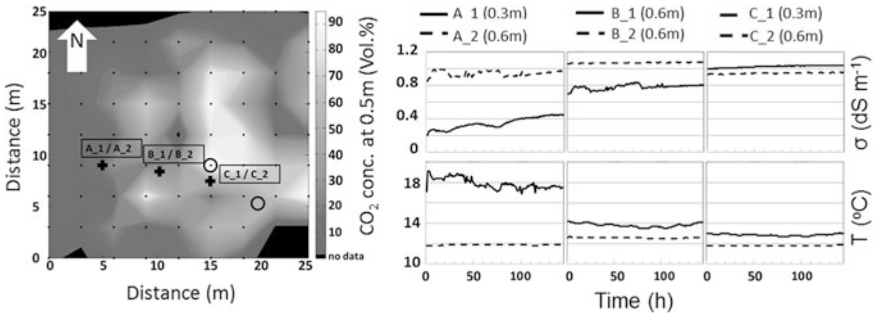

Fig. 5 *Left* Measured CO_2 concentration in 0.5 m depth on a 3 × 3 m grid at the field site in Starzach. Location of two mofettes (*circles*), location of six soil sensors (A_1, A_2, B_1,B_2,C_1, C_2; _1 indicate depth 0.3 m; _2 indicate 0.6 m) (*black crosses*), sample locations (*black dots*). *Right* Measured soil temperature (T) and electrical conductivity (σ) with in situ sensors placed in areas with low soil CO_2 concentration (10–30 vol%: soil sensors A_1 and A_2), intermediate concentration (31–60 vol%: soil sensors B_1 and B_2) and high concentration (61–80 vol%: soil sensors C_1 and C_2)

Figure 5 shows the measured CO_2 concentration at a depth of 0.5 m and some of the sensor data (T, σ) recorded at the site. The shallow sensors (0.3 m) exhibit a general trend of decreasing temperature and increasing electrical conductivity near the mofettes. In contrast, the deeper sensors show almost no variations. The following processes could be responsible for the observed trends: (1) Movement of groundwater along the degassing channels, which reduces the soil temperature and which in general has a higher electrical conductivity than rain water infiltrating the soil (Flechsig et al. 2010; Hölting and Coldeway 2013). (2) Higher dissolution effects in the soil near the mofettes. The higher amount of CO_2 leads to more dissolution of CO_2 in the soil water and the resulting increase in ion load occurs due to reactions of the CO_2 with the aquifer and soil matrix, causing an increase in electrical conductivity.

Based on the project experiences, a network of soil sensors placed above a CO_2 storage site can serve as a suitable monitoring tool. In the event of a leakage, the in situ sensors are able to identify subsurface areas of increased soil CO_2 concentrations. Although temperature and electrical conductivity could be detected in areas of increased CO_2 concentration at our investigated field site, the hydrogeological situation influencing the soil temperature is site-specific. Therefore, only electrical conductivity can be recommended as a more general parameter for indicating areas with potential CO_2 leakages.

To investigate the effect of variations in atmospheric parameters on intensity of mass fluxes from the two mofettes, a hood-shaped metal sheet with an opening for free gas outflow was placed over a mofette with an airtight seal. Gas fluxes out of mofettes are mainly driven by advection and therefore are much stronger than diffusive fluxes (Kämpf et al. 2013). The total amount of free gas outflow from a single mofette was estimated by simultaneously measuring flow velocity, static

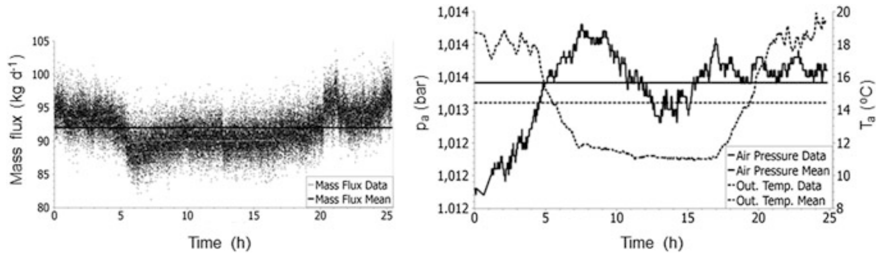

Fig. 6 *Left* Calculated mass flux from a mofette at the field site. The mean mass flux is 92 kg/d. *Right* Outside temperature (T_a) and air pressure (p_a) recorded at a nearby meteorological station over 24 h. Mean T_a for this period is 14.4 °C and mean p_a 1,013.4 mbar

pressure, and gas temperature. Measurements of the volumetric CO_2 content revealed a concentration of almost 100 vol.%. The resulting mass flux of CO_2 gas is shown in Fig. 6 for a period of 24 h compared with air temperature (T_a) and pressure (p_a), recorded at a nearby meteorological station. Variations in these meteorological parameters have no obvious influence on mass flux. However, the trend in air temperature correlates with the trend in mass flux. For smaller or more diffuse mass fluxes, changes in outside temperature and possibly also in air pressure could have a larger impact on mass flux intensity (Vodnik et al. 2009; Chiodini et al. 1998).

As a consequence, monitoring technologies should aim to measure small and diffusive-dominated mass fluxes, where natural variations that occur due to atmospheric parameters are known, so that anomalies can be clearly detected.

The project partner SARAD GmbH developed a new device for in situ flux measurements so that CO_2 flow can be directly measured in the ground and over large measurement distances.

2.3.3 Analysis of Isotopic Composition

Studies of the isotope signature of the soil CO_2 are essential to help distinguish between different CO_2 sources and to characterize the origin of soil CO_2.

The usefulness of analyzing the isotopic composition of soil CO_2 was tested at two sites with natural channel-like CO_2 degassing with CO_2 concentrations up to 90 vol%. In the Cheb Basin, the deep source of CO_2 (mantle derived) is confirmed by the isotope signature (Bräuer et al. 2008, 2011), whereas the origin of the CO_2 degassing in Starzach is still under discussion.

The measurement of the isotopic composition was validated to be an appropriate method to characterize the origin of CO_2 and was successfully used to confine clearly the boundaries of CO_2 soil degassing from areas with degassing of deep originated CO_2 in shallow subsurface (Fig. 7). However, it is a time-intensive, complex analysis method which requires profound expert knowledge.

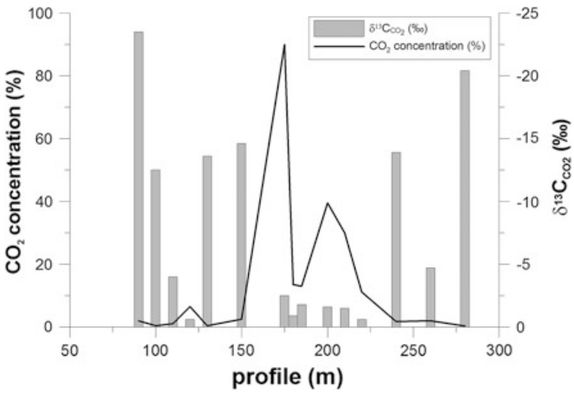

Fig. 7 Project results of investigations at the Cheb Basin site. A natural degassing zone was determined by increased CO_2 soil gas concentration and decreased $\delta\ ^{13}C_{co_2}$ values. The isotopic signature with a $\delta\ ^{13}C_{co_2}$ value of −2 ‰ measured in the degassing area indicates the deep magmatic source of CO_2

2.4 Validation of Methods for Atmospheric, Surface and Subsurface Monitoring

The methods applied for monitoring were evaluated by means of several criteria: robustness, availability, reliability, data accuracy, spatial resolution, spatial integration, temporal resolution, and effort based on practical requirements (e.g., equipment handling, data processing). For an assessment of the different monitoring techniques, the applicability of methods was classified into three groups: (−) limited compliance, (o) acceptable compliance, (+) appropriate compliance (Table 1).

2.4.1 Evaluation and Conclusion

The effectiveness of monitoring methods for CO_2 leakages depends on several factors including the contrast between the physical properties of CO_2 and the pore fluid displaced by CO_2, the lithology and structure of the reservoir, pore fluid pressure and temperature, field setups and surveys, well spacing, and injection patterns (Hagrey et al. 2013; Hoversten and Myer 2000). All methods applied within the MONACO project were evaluated and classified into three criteria:

- (o) **Useful supplementing method**: The application of methods is affiliated with various limitations with respect to the criteria and stand-alone application cannot guarantee suitable results. However, the method can provide additional information for joint interpretation.

Table 1 Validation of integrative methods applied in the MONACO project

Monitoring method	Atmospheric Monitoring				Surface Monitoring							Subsurface Monitoring						
	OP-FTIR Spectroscopy		Eddy Covariance	Atmospheric CO_2 conc. recording	Geophysical methods		Land Deforma-tion Monitoring	Mapping of soil properties		Measurement of soil gas		Geophysical methods		Measurement of soil gas			In- situ measurements	
	active	passive			Electro-magnetics	Self Poten-tial	Differential Global Satellite System (DGNSS)	Tempera-ture	Soil moisture	Soil gas conc. map.	Near-surface flux	Geoelectrics	Seismics	Isotope analyses	Radon conc.	Soil CO_2 conc. monitoring	Tempera-ture	Electical conductivity
Robustness	o	+	+	+	o	+	+	+	+	+	o	+	+	o	o	+	+	+
Availability	o unobstruc-ted sight	o unobstruc-ted sight	+	+	o	o/+	o	+	+	+	+	o/+	o/+	o	o	+	+	+
Reliability	+	+	+	+	+	+	o	o	o	+	o	+	+	+	o	+	+	o
Data accuracy and precision	+ calculated, integral value	o calculated, integral value	o calculated, integral value	+ measured	o integral apparent value	o various sources	+	o high spatial variance on small scales	o high spatial variance on small scales	o high spatial variance on small scales	+ high spatial variance, depends on meteorological conditions	+	+	+	o	+	o +/- 1°C	o +/- 10%
Spatial resolution	o large / medium scale	o large / medium scale	o medium scale	- medium scale	o medium scale	o medium scale	+ large scale	o medium/ small scale	o medium/ small scale	o medium/s mall scale	o medium/ small scale	+ large/ medium scale	+ large/ medium scale	- small scale	- small scale	+ large scale	+/- small scale	+/- small scale
Spatial integration	+ +	+ +	+ depends on quality of model	+	+	o	+	o	o	o	-	+	+	-	-	-/o	-	-
Temporal resolution	+	+	+	+	o	o	+	o	o	o	o/+	o	-	-	-	+	+	+
Effort																		
Equipment handling	+	+	+ needs exact setup and more maintenance	+	o Calibration important	+	o	+	+	+	+	+	+	o	+	-/+ demands subsurface installation, but easy to maintain	+/- demands subsurface installation	+/- demands soil specific calibration and subsurface installation
Data processing	+ complex data interpreta-tion including meteoro-logical modeling	o spectral analysis, complex data interpreta-tion including meteoro-logical modeling	o complex processing, lots of data	+ direct registration	o correction, filtering	+ fast and direct	o filtering procedures important, filtering of meteoro-logical influences	+ fast and direct	+ fast and direct	+ fast and direct	o flux calculation	o inversion, time lapse	-/o complex processing, time lapse	- time consu-ming, high laboratory effort	+	+ direct, less data	+ fast and direct	+ fast and direct
		expert [illegible]	expert [illegible]	basics	expert [illegible]						expert [illegible]	expert [illegible]	expert [illegible]	expert know-				

- (+) **Appropriate method**: Methods provide valuable information. However, the application has some restrictions/limitations, which have to be taken into account for interpretation.
- (++) **Favored method**: Applications of methods are suitable and provide significant results concerning assurance monitoring.

This classification for the common assurance monitoring tasks is shown in Table 2.

OP FTIR spectroscopy and EC method are considered to be suitable tools as part of an early warning monitoring concept, enabling detection of diffuse or focused CO_2 degassing over larger scales. OP FTIR spectroscopy can supply information on the distribution of CO_2 concentration under natural air conditions as an input parameter for the subsequent quantification of emission rates. The requirements for EC regarding wind conditions, instrumentation, survey design, implementation, and data processing are still very high. If the measuring requirements are met, the EC technique can provide flux information on a medium scale with sufficient temporal and spatial resolution. In addition, continuous wind speed measurements in combination with air CO_2 concentration registration at different heights, as well as CO_2 concentration monitoring with a handheld infrared gas analyzer, have some potential as an appropriate basic monitoring technique. However, due to the scale of

Table 2 Classification of the methods applied in MONACO project for nine pre-defined assurance monitoring tasks

Assurance monitoring tasks (near-surface applications)	Atmosphere				Ground surface								Subsurface			
	Optical remote sensing	Eddy Covariance Method	Handheld infrared gas analyzer	Distributed CO2 sensors	Ground based deformation studies	Soil gas concentrations	Soil gas composition	Soil flux measurement	Electromagnetics	Self-Potential	Soil moisture	Temperature mapping	Electrical resistivity tomography	Seismics	In-situ CO2 installations	Fluid sampling
Diffuse Degassing into the atmosphere	++	+	+	++				o								
Focussed degassing into the atmosphere	+	+	+	++				o								
Near surface soil contamination			o	o		++	++	++			o	o			++	++
Secondary seal integrity					o	+	++	++					+	+	++	++
Migration in subsurface					+	+	++	++		o		o	+	+	++	++
Preferential pathways					+	+	++	++	o	+	o	o	+	+	o	+
Structural Trapping					+			o	o	o			+	++		
Geological structures favoring degassing and accumulation									+	+			++	++		
Groundwater contamination with CO_2 or brine							+		+	o			++	o	++	++

++ favored method
\+ appropriate method
o useful supplementing method

CO_2 storage, these atmospheric methods could only be an integral part of a comprehensive monitoring concept consisting of methods that focus on other environmental domains or on different temporal and spatial scales.

Within the MONACO hierarchical approach the GNSS approach for detecting ground deformation was tested. It was shown that GNSS is suitable for continuous monitoring and investigation of contemporary ground surface deformation in mm range. However, information about height variation is based on distinct measurements at monitoring stations and cannot provide extensive information such as that obtained when using InSAR data.

Interpretation of various geophysical data can yield important information regarding fluid flow and transport processes in permeable near-surface layers, as well as structural and hydraulic properties. The selection of an appropriate method for the fulfillment of assurance monitoring tasks (such as detection of migration and preferential pathways, investigation of structural trapping) depends on site characteristics. The combination of geophysical methods, soil gas investigations and in situ installations concerning e.g., chemical properties of the groundwater, soil gas composition, soil gas ratios, and isotope ratios are necessary to improve the understanding of both gas migration processes and the resultant geophysical response functions, and to minimize ambiguities concerning the investigated geophysical parameter distribution. Furthermore, the influence of environmental conditions on geophysical and soil gas parameters needs to be considered when attempting to establish 'best practice' recommendation for CO_2 storage monitoring concepts.

The results of the MONACO project demonstrated that a successful near-surface monitoring plan should base on a hierarchical approach to cover different areas at different scales enabling a reliable detection of CO_2 migration paths and any leakages at the surface.

Acknowledgments This study was carried out within the framework of the "MONACO—Monitoring approach for geological CO_2 storage sites using a hierarchical observation concept" (grant ID: 03G0785) research project. Financial support provided by the German Federal Ministry of Education and Research (BMBF) in the frame of the Priority Program "Geotechnologien" is gratefully acknowledged. We cordially thank our native speaker C. Higgins for proofreading the manuscript. The authors would also like to thank C. Seeger, J. Poggenburg, A. Schossland, H. Kotas, G. Schmidt, K. Faiß and C. Sandig for technical support and T. Foken (Univ. Bayreuth), G. Burba, G. Fratini, F. Griessbaum and P. Martin (LI-COR Biosciences, Lincoln, Bad Homburg etc.) for theoretical input, fruitful exchange and technical advice.

References

Baldocchi D (2003) Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: past, present and future. Glob Change Biol 9(4):479–492. doi:10.1046/j.1365-2486.2003.00629.x

Benson SM (2006) Monitoring carbon dioxide sequestration in deep geological formations for inventory verification and carbon credits. https://pangea.stanford.edu/research/bensonlab/presentations/Monitoring%20Carbon%20Dioxide%20Sequestration%20in%20Deep%20Geological%20Formations%20for%20Inventory%20Verification%20and%20Carbon%20Credits.pdf

Bergmann P, Schmidt-Hattenberger C, Kiessling D, Rücker C, Labitzke T, Henninges J, Baumann G, Schütt H (2012) Surface-downhole electrical resistivity tomography applied to monitoring of CO_2 storage at Ketzin, Germany. Geophysics 77:B253–B267. doi:10.1190/geo2011-0515.1

Biggs J, Anthony E, Ebinger C (2009) Multiple inflation and deflation events at Kenyan volcanoes. East Afr Rift Geol 37(11):979–982. doi:10.1130/G30133A

Börner JH, Herdegren V, Börner R-U, Spitzer K (2010) Electromagnetic monitoring of CO_2 storage in deep saline aquifers—laboratory experiments and numerical simulations. In: Workshop on electromagnetic induction in the earth, Giza, Egypt, 18–24 Sept 2010

Börner JH, Herdegen V, Repke J-U, Spitzer K (2013) The impact of CO_2 on the electrical properties of water bearing porous media—laboratory experiments with respect to carbon capture and storage. Geophys Prospect 61(s1):446–460. doi:10.1111/j.1365-2478.2012.01129.x

Bourne S, Crouch S, Smith M (2014) A risk-based framework for measurement, monitoring and verification of the Quest CCS project, Alberta, Canada. Int J Greenhouse Gas Control 26:109–126. doi:http://dx.doi.org/10.1016/j.ijggc.2014.04.026

Bräuer K, Kämpf H, Niedermann S, Strauch G, Tesař J (2008) Natural laboratory NW Bohemia: comprehensive fluid studies between 1992 and 2005 used to trace geodynamic processes. Geochem Geophys Geosyst 9(4, Q04018):1–30. doi:10.1029/2007gc001921

Bräuer K, Kämpf H, Koch U, Strauch G (2011) Monthly monitoring of gas and isotope compositions in the free gas phase at degassing locations close to the Nový Kostel focal zone in the western Eger Rift, Czech Republic. Chem Geol 290(3–4):163–176. doi:10.1016/j.chemgeo.2011.09.012

Bruker (2014) Open path air monitoring system. Bruker optics GmbH. http://www.bruker.com/products/infrared-near-infrared-and-raman-spectroscopy/remote-sensing/ops/overview.html. Accessed 24 July 2014

Burba G (2013) Eddy covariance method for scientific, industrial, agricultural and regulatory applications (Personal communication at EGU 2014, Apr 2014). Lincoln, NE

Buselli G, Lu K (2001) Groundwater contamination monitoring with multichannel electrical and electromagnetic methods. J Appl Geophys 48(1):11–23. doi:10.1016/S0926-9851(01)00055-6

Byrdina S, Revil A, Pant SR, Koirala BP, Shrestha PL, Tiwari DR, Gautam UP, Shrestha K, Sapkota SN, Contraires S, Perrier F (2009) Dipolar self-potential anomaly associated with carbon dioxide and radon flux at Syabru-Bensi hot springs in central Nepal. J Geophys Res 114 (B10):1–14. doi:10.1029/2008jb006154

Chiodini G, Cioni R, Guidi M, Raco B, Marini L (1998) Soil CO_2 flux measurements in volcanic and geothermal areas. Appl Geochem 13(5):543–552. doi:http://dx.doi.org/10.1016/S0883-2927(97)00076-0

Dietrich P, Leven C (2006) Direct push technologies. In: Kirsch R (ed) Groundwater geophysics, vol 548. Springer, Berlin, pp 347–366. doi:10.1007/3-540-29387-6_11

EN_15483 (2008) Ambient air quality—atmospheric measurements near ground with FTIR spectroscopy. European Standard, CEN, Brussels

Ernstson K, Scherer U (1986) Self-potential variations with time and their relation to hydrogeologic and meteorological parameters. Geophysics 51(10):1967–1977. doi:10.1190/1.1442052

Etheridge D, Luhar A, Loh Z, Leuning R, Spencer D, Steele P, Zegelin S, Allison C, Krummel P, Leist M, van der Schoot M (2011) Atmospheric monitoring of the CO_2 CRC Otway project and lessons for large scale CO_2 storage projects. Energy Procedia 4:3666–3675. doi:http://dx.doi.org/10.1016/j.egypro.2011.02.298

Falge E, Baldocchi D, Olson R, Anthoni P, Aubinet M, Bernhofer C, Burba G, Ceulemans R, Clement R, Dolman H, Granier A, Gross P, Grünwald T, Hollinger D, Jensen N-O, Katul G, Keronen P, Kowlaski A, Lai C, Law B, Meyers T, Moncrieff J, Moors E, Munger J, Pilegaard K, Rannik Ü, Rebmann C, Suyker A, Tenhunen J, Tu K, Verma S, Vesala T, Wilson K, Wofsy S (2001) Gap filling strategies for defensible annual sums of net ecosystem exchange. Agric For Meteorol 107:43–69

Flechsig C, Bussert R, Rechner J, Schütze C, Kämpf H (2008) The Hartoušov Mofette Field in the Cheb Basin, Western Eger Rift (Czech Republic): a comperative geoelectric, sedimentologic and soil gas study of a magmatic diffuse degassing structure. Z Geol Wiss 36(3):177–193

Flechsig C, Fabig T, Rücker C, Schütze C (2010) Geoelectrical investigations in the Cheb Basin/W-Bohemia: an approach to evaluate the near-surface conductivity structure. Stud Geophys Geod 54(3):443–463. doi:10.1007/s11200-010-0026-6

Flesch TK, Wilson JD, Harper LA (2005) Deducing ground-to-air emissions from observed trace gas concentrations: a field trial with wind disturbance. J Appl Meteorol 44:475–484. doi:10.1175/JAM2214.1

Gal F, Brach M, Braibant G, Bény C, Michel K (2012) What can be learned from natural analogue studies in view of CO_2 leakage issues in carbon capture and storage applications? Geochemical case study of Sainte-Marguerite area (French Massif Central). Int J Greenhouse Gas Control 10:470–485. doi:10.1016/j.ijggc.2012.07.015

Georgiou P, Quick H, Jenkins H, Hayes C, Jensen D, Kelly J, Tollner D, Vale D, Price R, Thomson K (2007) Between a rock and a hard place: the science of geosequestration, Australian Government response report of the House of Representatives Standing Committee on Science and Innovation. Parliament of the Commonwealth of Australia, Canberra

Google Earth (2014) Hartousov 50.133494N 12.462030E, Date of image: 01 Jan 2004. Accessed 13 Aug 2014

Griffith DWT, Leuning R, Denmead OT, Jamie IM (2002) Air–land exchanges of CO_2, CH_4 and N_2O measured by FTIR spectrometry and micrometeorological techniques. Atmos Environ 36:1833–1842. doi:10.1016/S1352-2310(02)00139-5

Hagrey SAa, Strahser M, Rabbel W (2013) Seismic and geoelectric modeling studies of parameters controlling CO_2 geostorage in saline formations. Int J Greenhouse Gas Control 19:796–806. doi:10.1016/j.ijggc.2013.01.041

Harig R, Matz G (2001) Toxic cloud imaging by infrared spectrometry: a scanning FTIR system for identification and visualization. Field Anal Chem Technol 5(1–2):75–90. doi:10.1002/fact.1008

Harig R, Matz G, Rusch P (2006) Infrarot-Fernerkundung für die chemische Gefahrenabwehr. Zivilschutz-Forschung. Zivilschutz-Forschung, vol 58. Bundesamt für Bevölkerungsschutz und Katastrophenhilfe, Bonn

Hölting B, Coldeway WG (2013) Hydrogeologie: Einführung in die Allgemeine und Angewandte Hydrogeologie. Springer Spektrum, Berlin

Hoversten GM, Myer LR (2000) Monitoring of CO_2 sequestration using integrated geophysical and reservoir data. In: 5th international conference on greenhouse gas control technologies, Collingwood, Victoria, Australia, pp 305–310

Hovorka SD (2008) Surveillance of a geologic sequestration project: monitoring, validation, accounting. NETL webinar for the American Water Works Association

IEA (2012) Best practices for validating CO_2 geological storage: observations and guidance from the IEAGHG Weyburn-Midale CO_2 monitoring and storage project. Geoscience Publishing

IPCC (2005) Carbon capture and storage: Summary for policy makers and technical summary. Cambridge University Press

Jardani A, Revil A, Santos F, Fauchard C, Dupont JP (2007) Detection of preferential infiltration pathways in sinkholes using joint inversion of self-potential and EM34 conductivity data. Geophys Prospect 55(5):749–760. doi:10.1111/j.1365-2478.2007.00638.x

Kämpf H, Bräuer K, Schumann J, Hahne K, Strauch G (2013) CO_2 discharge in an active, non-volcanic continental rift area (Czech Republic): characterisation ($\delta^{13}C$, $^{3}He/^{4}He$) and quantification of diffuse and vent CO_2 emissions. Chemical Geology 339:71–83. doi:10.1016/j.chemgeo.2012.08.005

Kharaka YK, Thordsen JJ, Kakouros E, Ambats G, Herkelrath WN, Beers SR, Birkholzer JT, Apps JA, Spycher NF, Zheng L, Trautz RC, Rauch HW, Gullickson KS (2009) Changes in the chemistry of shallow groundwater related to the 2008 injection of CO_2 at the ZERT field site, Bozeman. Montana. Environ Earth Sci 60(2):273–284. doi:10.1007/s12665-009-0401-1

Knödel K, Lange G, Voigt H-J (2007) Environmental geology-handbook for field methods and case studies. Springer, Berlin

Lamert H, Geistlinger H, Werban U, Schütze C, Peter A, Hornbruch G, Schulz A, Pohlert M, Kalia S, Beyer M, Großmann J, Dahmke A, Dietrich P (2012) Feasibility of geoelectrical monitoring and multiphase modeling for process understanding of gaseous CO_2 injection into a shallow aquifer. Environ Earth Sci 67(2):447–462. doi:10.1007/s12665-012-1669-0

Leuning R, Etheridge D, Luhar A, Dunse B (2008) Atmospheric monitoring and verification technologies for CO_2 geosequestration. Int J Greenhouse Gas Control 2(3):401–414. doi:http://dx.doi.org/10.1016/j.ijggc.2008.01.002

Leven C, Weiß H, Vienken T, Dietrich P (2011) Direct-Push-Technologien – Effiziente Untersuchungsmethoden für die Untergrunderkundung. Grundwasser 16(4):221–234. doi:10.1007/s00767-011-0175-8

Lewicki JL, Hilley GE, Fischer ML, Pana L, Oldenburg CM, Dobeck L, Spangler L (2009) Detection of CO_2 leakage by eddy covariance during the ZERT project's CO_2 release experiments. Energy Procedia 1(1):2301–2306. doi:10.1016/j.egypro.2009.01.299

Pettinelli E, Beaubien S, Zaja A, Menghini A, Praticelli N, Mattei E, Di Matteo A, Annunziatellis A, Ciotoli G, Lombardi S (2010) Characterization of a CO_2 gas vent using various geophysical and geochemical methods. Geophysics 75(3):B137–B146. doi:10.1190/1.3420735

Reiche N, Westerkamp T, Lau S, Borsdorf H, Dietrich P, Schütze C (2014) Comparative study to evaluate three ground-based optical remote sensing techniques under field conditions by a gas tracer experiment. Environ Earth Sci 72(5):1435–1441. doi:10.1007/s12665-014-3312-8

Revil A, Pezard PA, Glover PWJ (1999a) Steaming potential in porous media: 1. Theory of the zeta potential. J Geophys Res 104(B6):2156–2202. doi:10.1029/1999JB900089

Revil A, Schwaeger H, Cathles LM, Manhardt PD (1999b) Streaming potential in porous media: 2. Theory and application to geothermal systems. J Geophys Res 104(B9):2156–2202. doi:10.1029/1999JB900090

Reynolds JM (2011) An introduction to applied and environmental geophysics. Wiley, Baffins Lane, Chichester, West Sussex POl9 IUD, England

Ringrose PS, Mathieson AS, Wright IW, Selama F, Hansen O, Bissell R, Saoula N, Midgley J (2013) The In Salah CO_2 storage project: lessons learned and knowledge transfer. Energy Procedia 37:6226-6236. doi:http://dx.doi.org/10.1016/j.egypro.2013.06.551

Sandig C, Sauer U, Bräuer K, Serfling U, Schütze C (2014) Comparative study of geophysical and soil–gas investigations at the Hartoušov (Czech Republic) natural CO_2 degassing site. Environ Earth Sci 72(5):1421–1434. doi:10.1007/s12665-014-3242-5

Sauer U, Schütze C, Leven C, Schlömer S, Dietrich P (2013) An integrative hierarchical monitoring approach applied at a natural analogue site to monitor CO_2 degassing areas. Acta Geotech 9(1):127–133. doi:10.1007/s11440-013-0224-9

Sauer U, Watanabe N, Singh A, Dietrich P, Kolditz O, Schütze C (2014) Joint interpretation of geoelectrical and soil-gas measurements for monitoring CO_2 releases at a natural analogue. Near Surface Geophysics 12(2007):165–178. doi:10.3997/1873-0604.2013052

Schütze C, Sauer U, Beyer K, Lamert H, Bräuer K, Strauch G, Flechsig C, Kämpf H, Dietrich P (2012) Natural analogues: a potential approach for developing reliable monitoring methods to understand subsurface CO_2 migration processes. Environ Earth Sci 67(2):411–423. doi:10.1007/s12665-012-1701-4

Schütze C, Dietrich P, Sauer U (2013) Diagnostic monitoring to identify preferential near-surface structures for CO_2 degassing into the atmosphere: Tools for investigations at different spatial scales validated at a natural analogue site. Int J Greenhouse Gas Control 18:285–295. doi:10.1016/j.ijggc.2013.07.006

Seto CJ, McRae GJ (2011) Reducing risk in basin scale CO_2 sequestration: a framework for integrated monitoring design. Environ Sci Technol 45(3):845–859. doi:10.1021/es102240w

Shuler P, Tang Y (2005) Atmospheric CO_2 monitoring systems. In: Thomas DC, Benson SM (eds) Carbon dioxide capture for storage in deep geologic formations—results from the CO_2 capture project geologic storage of carbon dioxide with monitoring and verification, vol 2. Elsevier, pp 1015–1030

Smaczny J, Clauser C, Klitzsch N, Blaschek R (2010) Numerical interpretation of self-potential (SP) data in the context of CO_2 storage. Paper presented at the EGU 2010 (May 2-7, 2010), Vienna, Austria

Sprunt ES, Mercer TB, Djabbarah NF (1994) Streaming potential from multiphase flow. Geophysics 59(5):707–711. doi:10.1190/1.1443628

UNEP (2006) Can carbon dioxide storage help cut greenhouse emissions? A Simplified guide to the IPCC's Special report on carbon dioxide capture and storage

Verdon JP, Kendall J-M, Stork AL, Chadwick RA, White DJ, Bissell RC (2013) Comparison of geomechanical deformation induced by megatonne-scale CO_2 storage at Sleipner, Weyburn, and in Salah. Proc Natl Acad Sci 110(30):E2762–E2771. doi:10.1073/pnas.1302156110

Vodnik D, Videmšek U, Pintar M, Maček I, Pfanz H (2009) The characteristics of soil CO_2 fluxes at a site with natural CO_2 enrichment. Geoderma 150(1–2):32–37. doi:10.1016/j.geoderma.2009.01.005

Weinlich FH, Bräuer K, Kämpf H, Strauch G, Tesař J, Weise SM (1999) An active subcontinental mantle volatile system in the western Eger rift, Central Europe: gas flux, isotopic (He, C, and N) and compositional fingerprints. Geochimica et Cosmochimica Acta 63(21):3653–3671. doi: http://dx.doi.org/10.1016/S0016-7037(99)00187-8

White JA, Chiaramonte L, Ezzedine S, Foxall W, Hao Y, Ramirez A, McNab W (2014) Geomechanical behavior of the reservoir and caprock system at the in Salah CO_2 storage project. Proc Natl Acad Sci 111(24):8747–8752. doi:10.1073/pnas.1316465111

Zhao W, Amelung F, Dixon T (2012) Monitoring ground deformation on carbon sequestration reservoirs in North America. In: Fringe 2011 workshop, Frascati, Italy, 2012. vol SP-697. ESA

Zlotnicki J, Nishida Y (2003) Review on morphological insights of self-potential anomalies on volcanoes. Surv Geophys 24(4):291–338. doi:10.1023/B:GEOP.0000004188.67923.ac

Zschornack L, Leven C (2012) Minimal invasive methods. In: Kästner M, Braeckevelt M, Döberl G et al. (eds) Model-driven soil probing, site assessment and evaluation—guidance on technologies, vol 307. Sapienza Università Editrice Rome, Italy, pp 337–388

http://www.springer.com/978-3-319-13929-6

Geological Storage of CO2 – Long Term Security
Aspects
GEOTECHNOLOGIEN Science Report No. 22
Liebscher, A.; Münch, U. (Eds.)
2015, X, 245 p. 129 illus., 104 illus. in color., Hardcover
ISBN: 978-3-319-13929-6