ATLAS

on geological storage of carbon dioxide in South Africa

Abbreviations

CBM coalbed methane
CCS carbon capture and storage
CO2CRC Cooperative Research Centre for Greenhouse Gas Technologies (Australia)
CSIR Council for Scientific and Industrial Research
CSLF Carbon Sequestration Leadership Forum
DEA Department of Environmental Affairs and Tourism
DME Department of Minerals and Energy (pre mid-2009)
DMR Department of Mineral Resources (post mid-2009)
DoE Department of Energy (post mid-2009)
ECBM enhanced coalbed methane (recovery)
EGR enhanced gas recovery
EOR enhanced oil recovery
IEA International Energy Agency
IPCC Intergovernmental Panel on Climate Change
LTMS Long-term Mitigation Scenarios
MMV measuring, monitoring and verification (e.g., CO₂ in the subsurface)
UCG underground coal gasification
Ma million years (annums), normally used to denote geological age
Gg giga gramme
Gt gigatonne (1 Gt = 1 000 000 000 t or 1 000 Mt)
Mt million tonne
Atlas on geological storage of carbon dioxide in South Africa

Compiled by Marthinus Cloete
Council for Geoscience
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Minister’s Foreword

I am proud to present to you the first Atlas on the geological storage of carbon dioxide in Africa. The *Atlas on Geological Storage of Carbon Dioxide in South Africa* represents the first major milestone in identifying potential storage sites in South Africa.

The production of this Atlas is a result of the cooperation and partnership between Government, State-Owned Entities and the private sector. These include the South African National Energy Research Institute, PetroSA, Anglo American, Eskom, Sasol, the Council for Geoscience and the Petroleum Agency of South Africa. The salient outputs of this Atlas will be incorporated into the work programme of the newly established South African Centre for Carbon Capture and Storage.

The Atlas provides an overview of our country’s energy economy, a roadmap on carbon capture and storage, as well as the progress made to date in this regard. It includes geological maps and also makes reference to the potential and estimated carbon dioxide storage capacities of the geological formations that are found in our country.

South Africa endeavours to play its part in the global effort to mitigate greenhouse gas emissions that are the main cause of climate change. We have domestic targets and mechanisms for increasing the usage of renewable energies and for achieving greater energy efficiency. However, our energy economy is largely based on its indigenous fossil fuels — primarily coal. Not only does coal provide the basis for electricity and the production of liquid fuels, it also serves as a foundation for most of our industries and, subsequently, forms a substantial portion of our exports.

Our coal industry contributes significantly to employment opportunities, income generation, as well as accounting for huge foreign-exchange earnings for the country. We are firmly resolved to increase the use of renewable energy in a bid to diversify our energy mix; however, we recognise that coal will continue to be the basis for the provision of most of our primary energy needs for the next few decades.

It is against this backdrop that Government, through the Department of Energy, has proactively and vigorously engaged in the difficult issue of mitigating greenhouse gas emissions by carbon capture and storage (CCS). Our commitment is demonstrated by the fact that we currently serve as the Vice Chair of both the Policy Group and the Technical Group of the Carbon Sequestration Leadership Forum (CSLF). The same interest is demonstrated in the use of other clean coal technologies, which are initiatives in addition to the all-important issues of renewable energy and energy efficiency programmes.

During 2007, South Africa, through the Department of Environmental Affairs, released the Long-Term Mitigation Scenarios report that described a number of actions that have to be taken in order to decrease national carbon dioxide emissions between the present and 2050. Included in these alternative interventions is the use of carbon capture and storage (CCS) technologies. Carbon capture and storage is usually done by separating carbon dioxide, transporting it and subsequently injecting it into deep geological formations — where it should remain securely stored. Research on the carbon storage potential of a country or region obviously has to take cognisance of the peculiarity of each country or region with regard to its geological conditions. South Africa is no exception.
Although the mitigation of carbon dioxide is primarily an energy industry issue, it, nevertheless, has an impact on other government portfolios. This Atlas, therefore, makes a significant contribution to the national strategy to reduce greenhouse gas emissions, currently being developed by the Department of Environmental Affairs, in consultation with other government departments.

While this Atlas is aimed at providing easily accessible information to decision-makers, a detailed technical report is also available for use by specialists as a basis for future work in this important area. It is envisaged that more studies will need to be conducted to refine the geological storage capacities that will specifically require more basin- and site-specific information.

I want to congratulate and thank all those who have actively contributed to the success of this project. The partnership between the public and the private sector in this groundbreaking endeavour clearly demonstrates that together we can indeed do more!

Ms Dipuo Peters, MP
Minister of Energy
In order to mitigate climate change, the world is moving towards ambitious goals for the reduction of carbon dioxide emissions. However, carbon dioxide emissions arise largely through the use of fossil fuels to provide energy that is, in turn, an essential ingredient for achieving economic and social development. Similar to the countries that rely heavily on their fossil fuel resources for energy, South Africa is exploring various ways to ‘decarbonise’ its energy supplies over the coming decades without compromising energy security.

A number of opportunities for decarbonisation have been identified globally. These include improved energy efficiency, implementing cleaner coal technologies and the rapid deployment of renewable and nuclear energy. Each of these opportunities is being investigated in order to determine the extent to which they can contribute towards the mitigation of greenhouse gas emissions in South Africa. These opportunities have their unique challenges and all of the opportunities will need to be harnessed if the joint goals of climate change mitigation and energy security are to be achieved.

Within the realm of cleaner coal technologies, the capture and storage of carbon dioxide — known as ‘carbon capture and storage’, or CCS — is proposed as a technology that has the potential to significantly reduce the carbon footprint of various types of fossil fuel-fired installations. There are a number of variants of this technology, depending on the source of the carbon dioxide and the type of storage available. Full-scale capture technologies for different sources are being investigated internationally; however, the type of storage available will depend mostly on local conditions. South Africa’s emissions of carbon dioxide are currently estimated at over 400 Mt per annum, including both point and diffuse sources. It is apparent that South Africa will remain reliant on fossil fuels for the next few decades until other energy sources can gradually replace these high-carbon fuels. Carbon capture and storage is therefore regarded as a transition measure from fossil fuels to renewable/nuclear energies.

Storage opportunities may be sought for smaller or shorter-term point sources, but also for larger or longer-term point sources. For example, a project that emits 1 Mt of carbon dioxide per year for 20 years would require proven storage in the order of 20 Mt (0.02 Gt), while a project that emits 30 Mt of carbon dioxide per year for 50 years would require proven storage in the order of 1 500 Mt (1.5 Gt).

A previous study into South Africa’s potential for storing carbon dioxide was undertaken at the behest of the then Department of Minerals and Energy by the CSIR and released during 2004. At a theoretical level, the study determined that South Africa could have substantial storage capacity in geological formations. This Atlas, funded by multiple stakeholders, was initiated in order to further define the geological storage capacity that can be found in South Africa.

In the preparation of the Atlas, the Council for Geoscience and the Petroleum Agency of South Africa have utilised existing information, including seismic and historical drill-core data from the onshore and offshore sedimentary basins, in order to estimate the storage potential of depleted oil and gas reservoirs, deep and unmineable coal seams and deep saline formations.
Part 1 of this Atlas provides an introduction to South Africa’s energy economy and greenhouse gas emissions. Part 2 elaborates on the geological conditions required for successful storage and methods of estimation. Part 3 provides detailed insights for each of the three storage types that have been investigated.

The theoretical potential identified by the earlier study for deep saline formations in the Karoo Supergroup has been confounded by the low permeability and porosity measurements obtained. In addition, the relatively small estimated storage capacities (of about 1 Gt each) of depleted oil and gas reservoirs and deep, unmineable coal seams have been confirmed. Nonetheless, these areas may provide unique storage opportunities for smaller point sources.

This Atlas has expanded on previous studies and identified new storage potential in the onshore and offshore Mesozoic basins that run along the coast of South Africa. In summary, the Atlas identifies approximately 150 Gt of potential storage in the three storage types (deep saline formations, unmineable coal seams and depleted oil and gas reservoirs) of which about 98% is offshore. These investigations also indicate that the Karoo Basin should be considered as non-conventional storage and requires further investigation before it could be considered a potential storage site.

The Atlas indicates that a major portion of the storage is distant from current emission sources. Further techno-economic evaluations will be required in order to define the ultimate role of carbon capture and storage in South Africa’s energy mix.

While this Atlas represents a significant advance on previous estimates, it is pertinent to draw attention to the question of certainty. Other atlases have developed a variety of indicators in order to reflect the relative confidence that can be placed in the data (and hence the estimated capacity calculations). This Atlas uses an indicator that yields confidence levels for the various estimates that range from 1 (low) to 9 (high). The uncertainty largely reflects the paucity of borehole data and seismic surveys.

Significant investments will be required in order to realise the commercialisation of carbon capture and storage technology in South Africa. Investment decisions are likely to follow an iterative process between estimating the costs for matching sources to potential sinks and obtaining further geological information, as well as investing in alternative mitigation options. This last consideration really only applies in the shorter term, if one accepts the earlier assertion that all types of mitigation will be required in order to address both climate change mitigation and energy security. Overall, long time frames are required to characterise potential storage reservoirs, develop the necessary skills and technology base and to consult with the public. This Atlas is a key component of the programme that is intended to develop a full-scale CCS deployment beyond 2025.
Part One
Introduction

South Africa's energy economy

Similar to many other countries in the world, South Africa is reliant on fossil fuels for most of its primary energy supply. Approximately 90% of primary energy is derived from fossil fuels (coal, oil and gas), and the absolute amount is likely to increase with the advent of new coal-fired electricity-generating stations and new coal/gas-to-liquid-fuel plants to supply growing demand.

During 2009, coal contributed 65.9% to South Africa’s primary energy supply, oil contributed 21.5% and gas comprised only about 2.8%, as shown in Figure 1.1. Although most of the oil is imported, a small percentage of it is sourced from the Mossel Bay offshore oil and gas fields.

The gas contribution to the primary energy supply currently comes from two sources, Mossel Bay and Mozambique. All of the gas from Mossel Bay is converted into liquid fuels and other products by PetroSA, while the gas from Mozambique is also used by Sasol in the gas-to-liquids process and is sold for industrial and household use.

In addition to fossil fuels, nuclear energy currently contributes about 1.9% of primary energy supply through the generation of electricity at Koeberg Power Station. The process to introduce further nuclear stations is being led by the South African Government and Eskom.

The current contribution from renewable energy (7.6%) to primary energy supply is principally through the use of biofuels in rural areas, which is unsustainable without regeneration. The South African Government has established a target that will increase the contribution from renewable energy sources by 2013 and has been supported in this initiative by the National Energy Regulator of South Africa who introduced renewable energy feed-in tariffs to the electrical grid.

![Figure 1.1 — The relative contributions of the different energy types towards South Africa's primary energy consumption.](image-url)
Electricity is vital to the economy of South Africa. Ninety-two per cent of South Africa’s electricity is generated from coal.
Careful planning is necessary to transition South Africa to a low-carbon energy supply.

Renewable energy is widely advocated as the solution to mitigate greenhouse gas emissions. In fact, harnessing renewable energies is required in the longer term, irrespective of the role it can play in addressing climate change, as the availability of fossil fuels declines. However, even aggressive technology development and deployment of renewables will not be sufficient to supply all the projected energy demands in the medium term.

Notwithstanding the increased roll-out of renewable energies and energy efficiency measures, reputable bodies, such as the International Energy Agency have forecast a global increase in the use of fossil fuels under a business-as-usual scenario — most of the increase originating in developing countries.

The conversion of these primary energy sources is illustrated in Figure 1.2. Nearly 92% of South Africa’s electricity is generated from coal, while nuclear energy provides 4.2% of the electricity supply and hydro energy 2.4%. In the case of hydro energy, 1.7% of the capacity is pumped storage (Figure 1.2), whereby the water is pumped uphill during off-peak hours, creating a gravitational energy store. During peak demand for electricity, the stored water is released to drive turbines, thus supplementing the electricity generated from other sources.

Electricity is the essential driver for the South African economy and for the upliftment of the poor, both through job creation and the national electrification programme. The generation/demand shortfall that manifested itself early 2008 illustrated the impediments that an electricity deficit has on economic development, poverty alleviation, job creation, transport and the convenience of daily living.

South Africa’s current primary energy profile directly reflects its natural resource base, which has been developed over the last few centuries. With tight supply margins and under financial constraints, South Africa has little room to manoeuvre with respect to its energy supply. Given the long life of the assets and planning lead times associated with building new energy infrastructure, it requires well considered planning, trade-offs and social changes to transform South Africa to a low-carbon energy supply. Carbon capture and storage may provide an option to reduce CO₂ emissions from fossil fuel-fired installations at a future date.
The Lethabo Power Station in the Free State Province burns coal with a calorific value of 15–16 MJ/kg and an ash content of 42 per cent. It is the only power station in the world running on such low-grade coal.
South Africa faces many challenges on its path to reduce its carbon emissions.

**Carbon dioxide and climate change**

Accelerated climate change has been identified globally as having the potential to undermine all human endeavour, while the release of greenhouse gases as a result of human activities is now widely accepted to be contributing to this effect (Figure 1.3).

Due to the complexity of the interactions in the earth–atmosphere system, scientists and policy-makers compare the various greenhouse gases based on their radiative forcing in order to determine which greenhouse gases to address. In this way, it has been possible to identify carbon dioxide (CO₂), followed by methane (CH₄) and nitrous oxide (N₂O) as being the main contributors to the greenhouse effect. In South Africa, CO₂ contributed to more than 80% of the total for the three main greenhouse gases for both 1990 and 1994, as recorded in the national inventory.

Fossil fuel use is the primary source of the increased atmospheric concentrations of CO₂ since the pre-industrial period. Fossil fuels are used around the world as a source of energy. Particularly in South Africa, we have abundant indigenous coal reserves that are used in electricity generation, in the production of liquid fuels and also for a direct supply of heat and steam in other industrial processes. The latest greenhouse gas emission levels are currently being revised by the Department of Environmental Affairs. However, a United Nations Framework Convention on Climate Change (UNFCCC) lists the CO₂ emissions from South Africa at 316 million tonnes per year for the year 1995. Current emissions are estimated as greater than 400 million tonnes per year.

Figure 1.3 — Contribution of the different sectors in South Africa to the total emissions (CO₂ equivalents), as estimated in 1994.
South Africa has abundant indigenous coal reserves, part of which are used in the production of liquid fuels (Sasol plant, Secunda).
South Africa can reduce its CO₂ emissions considerably in the future.

There are clear benefits to utilising a country's indigenous resources, such as lower costs, security of supply and local economic activity with its associated employment. However, the use of coal in South Africa has also been associated with environmental impacts.

Similar to previous efforts by governments and industry to curb emissions of particulates, and sulphur and nitrogen oxides, attention is now being given to the mitigation of CO₂, the distinction being that the reduction of greenhouse gases is a global and not merely a regional matter.

To this end, the United Nations Framework Convention on Climate Change and its Kyoto Protocol address international responsibilities and mechanisms to limit the global emissions of greenhouse gases.

At the Climate Change Summit held in Johannesburg during 2009, the Department of Environmental Affairs announced South Africa's aspiration for its CO₂ emissions to increase until 2020–25, plateau for a decade, and then decrease in real terms after 2030–35. During the Copenhagen UNFCCC 2009 meeting, the South African President subsequently announced that South Africa could decrease its emissions compared to business as usual, provided that international support was made available to implement such a mitigation programme.

There are many challenges for South Africa to pursue a low-carbon development path. Alternatives to the use of coal in South Africa all have their own costs and benefits. The opportunities for energy efficiency, and the cleaner use of coal and other alternatives have been outlined in the 2007 'Long-Term Mitigation Scenarios' (LTMS) developed by the then Department of Environmental Affairs and Tourism (DEAT). All of these opportunities will have to be realised in order to achieve ambitious global emission reduction goals by 2050.

Carbon capture and storage (CCS) is one technological solution that may significantly reduce CO₂ emissions. The technology has been demonstrated at a small scale and is currently used in niche industrial and commercial applications around the world. There is also a global commitment to demonstrating the integrated technology at appropriate scale in the coming decade for technically feasible sources. It is important for South Africa's long-term development plans to establish whether carbon capture and storage has a potential role to play in a domestic greenhouse gas mitigation strategy.
Research has shown that South Africa has the potential to store carbon dioxide in deep geological formations.

The CCS Roadmap of the Centre for Carbon Capture and Storage

From identifying South Africa’s expected CO₂ storage potential, the South African Carbon Capture and Storage Roadmap provides a phased outline of the work required for achieving a commercial roll-out of CCS technology in South Africa. Once the geology of a storage reservoir has been characterised, the intention is to consider test injections by 2016 and potentially scale up the operations to demonstration scale up to 2020 in order to enable commercial deployment by around 2025. This process is necessary in order to develop the local expertise and information required to execute the technology, to test the regulatory system and to understand public acceptability. The time frame and scale of the five phases are depicted in Figure 1.4.

Figure 1.4 — The Carbon Capture and Storage Roadmap for South Africa.
In 2009 a Centre for Carbon Capture and Storage was established in South Africa.

**Institutional framework**

South Africa’s participation in the United Nations Framework Convention on Climate Change is led by the Department of Environmental Affairs.

The Department is informed in this regard by its National Committee for Climate Change that comprises local stakeholders. During 2007, the then Department of Environmental Affairs and Tourism released a Long-Term Mitigation Scenario (LTMS) study that placed into perspective all the measures that South Africa could undertake to limit the emissions of greenhouse gases. Carbon capture and storage was projected to contribute around 5% of the required emission reductions, the relatively low value being chosen to reflect the high level of uncertainty currently associated with the application of the technology in South Africa.

In 2007, the South African Cabinet adopted a policy framework based on the four strategic options analysed in the LTMS process, which largely emphasises energy efficiency and diversification of the energy sector away from fossil fuels. In this respect, climate change mitigation is supported by the policies published by the Department of Energy, for example, South Africa’s White Paper on Energy Policy, as well as the Renewable Energy White Paper.

Currently, the Department of Environmental Affairs is developing a climate change response policy. This Atlas is part of the effort to contextualise the potential for application of carbon capture and storage in South Africa and to illustrate the feasibility of local implementation.

A regulatory system for carbon capture and storage does not yet exist in South Africa. However, the regulatory system for the extraction of minerals is well developed and the administration of those regulations falls under the Department of Mineral Resources and its regional offices. An investigation into the regulatory gaps for carbon capture and storage was initiated by the Department of Energy during 2009.

This Atlas represents a significant milestone, contributing to the understanding of what the expected geological storage potential may be in South Africa. The outputs of this Atlas and the more detailed information addressed in the accompanying technical report will form the foundation of future carbon capture and storage work in South Africa.

In March 2009, the South African Centre for Carbon Capture and Storage was established under the auspices of the South African National Energy Research Institute. The Centre’s mandate is to build both human and technical capacity for the implementation of carbon capture and storage. The South African Centre for Carbon Capture and Storage is expected to continue with the characterisation of storage reservoirs and storage demonstration.
A typical Karoo landscape. Much hope has been pinned on the Karoo Basin providing sufficient pore space to store South Africa’s future CO₂ emissions, but its geological development seems to preclude its use for conventional storage applications. Research, however, may still show if unconventional storage space is available.
Carbon capture and storage technology

Geological storage of carbon dioxide (CO₂) is the process whereby the gas is captured and separated from an industrial source, is transported and injected into deep geological formations for long-term storage and finally is measured, monitored and verified to ensure that the CO₂ stays in the storage formation. The usual geological requirements for the right place to store CO₂ include having a porous and permeable reservoir rock to allow injection and storage of the CO₂, overlain by an impermeable seal rock to retain the injected CO₂ in the geological subsurface.

Of the four components mentioned above, the storage component will be unique to the geology of each country. The technologies of capture, transport and monitoring are all under investigation internationally, and developments in this regard are tracked through international organisations and cooperative research, but identification of suitable storage formations has to be carried out locally.

The Atlas is a significant milestone in this process — building upon previous research undertaken at the behest of the then Department of Minerals and Energy (DME) and released by the CSIR in 2004 (Figure 1.5). This initial assessment identified the possibility that South Africa could have substantial storage capacity. This Atlas has made use of available basin-level information to further refine South Africa’s storage capacity estimations. Much more work, however, will be required to refine these estimates to the point where specific storage sites can be matched with South Africa’s point source emissions of CO₂.
$\text{CO}_2$ can be stored in depleted oil and gas fields. The PA platform of PetroSA is situated approximately 90 km offshore of Mossel Bay. The platform is operating in the oil and gas fields of the Outeniqua Basin, which could potentially be used for $\text{CO}_2$ storage in the future.
Geological storage of carbon dioxide

Geological storage of CO$_2$ involves the injection of anthropogenic (or manmade) CO$_2$ into underground formations where it can be securely and permanently stored. This is analogous to how hydrocarbons (oil and gas) are naturally trapped in underground reservoirs. Geological storage of CO$_2$ can target depleted oil and gas reservoirs or deep saline formations (Figure 2.1), where it becomes trapped in the pore spaces between the grains of the sedimentary rock, and also unmineable coal seams, where it displaces the coalbed methane adsorbed onto coal surfaces.

The geological storage of CO$_2$ has been used for years to enhance the production of oil and gas fields, while the storage of gas and other substances in geological reservoirs has also been undertaken for decades. The same geological conditions that have kept economically viable gas and oil accumulations in the sub-surface for millions of years are now being applied for the storage of CO$_2$.

Geological storage of CO$_2$ does not present insurmountable technical barriers. In fact, the storage of CO$_2$ is currently being demonstrated on a commercial scale at a number of sites around the world.

The Statoil-operated Sleipner field in the North Sea was the first case of industrial-scale CO$_2$ storage and approximately 1 million tonnes of CO$_2$ per year have been sequestered at the Sleipner field in deep saline formations above the natural gas reservoir since 1996. Another significant large-scale CO$_2$ storage project is located in Weyburn, Canada. The project has been injecting CO$_2$ into the Weyburn oil field since 2000 as part of an enhanced oil-recovery process to extend the life of the field. To date, Weyburn has injected 11 million tonnes of CO$_2$, most recently at a rate of 3 million tonnes per year.

Figure 2.1 — Geological storage options in depleted oil and gas fields (1), with enhanced oil (EOR) and gas (EGR) recovery (2), in deep (>800 m) saline formations (3), and in unmineable coal seams with enhanced coalbed methane (ECBM) production (4 and 5).
Unlike these thick, shallow coalbeds that are mined by the opencast method, coalbeds can also be found at depths regarded as too deep for conventional mining. Such coalbeds become eligible for ECBM recovery, implying that methane gas can be harvested by flushing it out with CO₂ and having the latter safely stored.

Two problems of storing CO₂ in so-called ‘unmineable coalbeds’ are: (1) economic conditions may change, which would render the coal mineable, and (2) a relatively new technology called ‘underground coal gasification’ (UCG) harvests the energy by gasifying the coal whilst it is still deep in the ground and piping off the resultant gas (Kleinkopje Colliery near Witbank).
South Africa has only limited CO₂ storage space in its maturing oil and gas fields due to their limited size; however, saline formations associated with these petroleum-bearing formations hold potential, but would require considerable development and investment.

Storage in mature/depleted oil and gas reservoirs

CO₂ can be geologically stored in oil and gas fields once they have been depleted and are no longer producing, or while they are still producing in order to enhance oil and gas recovery (EOR and EGR). The main advantages of storage in depleted oil and gas fields are that the containment potential of the site has been proven by the retention of hydrocarbons for millions of years and that there are typically large amounts of geological and engineering data available for detailed site characterisation.

Replacing coalbed methane in deep, unmineable coal seams

Unmineable coal seams are those deemed too deep or too thin to be mined economically. It should be kept in mind that the definition of 'unmineable' may change with technological developments or economic conditions.

All coals have varying amounts of methane adsorbed onto microscopic surfaces. Boreholes can be drilled into these coal seams to recover this coalbed methane (CBM). Initial CBM recovery methods, such as dewatering and depressurisation, leave a considerable amount of methane behind in the coal beds. Enhanced coalbed methane (ECBM) recovery can be achieved by flushing the coal with CO₂. Depending on the coal rank, between three to thirteen molecules of CO₂ are preferentially adsorbed onto the coal for each molecule of methane that is released, thereby providing an excellent storage site for CO₂. However, the penetration of the CO₂ into the coal seam may be limited, depending on how much the coal 'swells' during the process and some of the techniques for depressuring the coal (rock fracturing) may reduce the integrity of the storage. Research into CO₂ storage in coal is not yet at a mature stage and further work needs to be conducted to fully understand the processes involved and the most suitable coal characteristics for CO₂ storage.

Storage in deep saline formations

Storing CO₂ in deep sedimentary formations, and ensuring that it remains there, requires a layered rock mass that is deeply buried, sufficiently permeable to receive the injected CO₂ and functions as a reservoir, which is overlain by impermeable caprock to prevent the CO₂ from escaping. Often, one or more sides of the formation remain open, allowing for some lateral displacement beneath the caprock of formation water by the injected CO₂.

Once injected into the storage formation, the compressed CO₂ fills the spaces between the pores (Figure 2.2). A combination of physical and geochemical trapping mechanisms act to retain the CO₂ underground. Physical trapping mechanisms involve capillary forces that retain the CO₂ in the pore spaces of the formation, while geochemical trapping occurs as the CO₂ reacts with in situ saline formation water and host rock to form stable carbonate minerals. These reactions, however, may only occur over long periods of time.
Figure 2.2 — Microscopic view of a medium-grained Karoo sandstone. The grains of this rock are much less tightly packed than those of mudstones/siltstones (Figure 2.3) and locally there are intergranular voids. The voids in this sample are filled by red epoxy cement. At depths greater than 800 m these voids would likely be filled with saline water that is unsuitable for drinking and agricultural use. Injected CO₂ would displace most of the water and reside in the void spaces, eventually dissolving and reacting with the formation water and surrounding rocks to form stable carbonate minerals.

Figure 2.3 — Microscopic view of a Karoo siltstone. Fine-grained particles of quartz and feldspar (clear) are suspended in a yellow-brown matrix of clay minerals, viewed in polarised light. The grains forming this rock are densely packed with hardly any interconnected pore spaces. The low permeability of these rocks make them ideal barriers to prevent the migration of CO₂ out of target storage formations.

Figure 2.4 — Electron micrograph of steel furnace slag. Various calcium- and/or magnesium-containing mineral phases are present in slag which may react with CO₂ to form solid carbonate minerals.
The secure storage of CO₂ in saline or hydrocarbon formations would require appropriate rock formations at depths below 800 m.

CO₂ storage in deep saline formations or hydrocarbon reservoirs is generally accepted to take place at depths below 800 m, or where the ambient pressures and temperatures will result in the CO₂ being in a supercritical state, i.e. in a dense fluid form where it is neither gas nor liquid. In the supercritical state the CO₂ is able to dissolve more readily in formation water and react with cations to form stable, mineral compounds. At shallower depths (i.e. lower temperatures and pressures where the CO₂ is in a subcritical state — in liquid form), it is immiscible with formation water, and therefore less soluble and less available to mineral-forming reactions.

A systematic evaluation of these deeply buried formations and their capacity to accept and retain the injected CO₂ is an essential part of the site assessment before CO₂ can be injected. Typically, geological processes, such as diagenesis and metamorphism, will diminish rock porosity and permeability, whereas tectonism and magmatism will lead to jointing, faulting and cross-cutting relationships which will generally compromise secure storage.

CO₂ injection sites constitute highly engineered systems. The injection wells consist of several casings that ensure that the CO₂ only enters the pre-determined injection zones and does not enter the rock above that zone where it could contaminate sources of drinking water, which are much shallower than the prospective CO₂ storage formations. Various technologies that are required to safely inject CO₂ into these deep geological formations exist today and are adopted from technologies and industrial best practices that are routinely used in countries with natural gas production industries. While CO₂ injection can be considered an established technology in the EOR business, injection on a scale large enough for the purpose of global climate change mitigation requires further development, and field demonstration of more advanced drilling and injection techniques to allow for the greatest possible utilisation of available storage reservoirs.

Other possible future carbon dioxide storage options

Less mature options for geological storage of CO₂ include basaltic rocks and shale. However, much more research is necessary before these can be considered feasible technologies. Shale, the most common type of sedimentary rock, usually contains some organic material which provides an adsorption substrate for CO₂ storage similar to CO₂ storage in coal seams. Because of the very low permeability of shale, research is focused on achieving economically viable CO₂ injection rates (Figure 2.3).

Although only at the research stage, mineral carbonation also represents a CO₂ conversion technology which offers a safe and permanent storage method for CO₂ disposal. It involves the chemical reaction of calcium and magnesium from widely available materials (e.g., primary mineral deposits, industrial wastes) with CO₂ to form stable carbonate minerals. While this technology is proven, existing processes are not yet cost effective (Figure 2.4).
It is anticipated that certain agricultural sectors, especially those of the southwestern Cape, may be increasingly exposed to a drier environment if global warming is left unabated.
**Safe storage of carbon dioxide**

There are few inherent risks to the geological storage of CO₂. This is based on the fact that it is a colourless and odourless, non-toxic, naturally occurring gas. Presently, the earth’s atmosphere is composed of a little less than 0.04% CO₂. This small amount plays an important role in maintaining the natural greenhouse balance that makes earth hospitable to life. Carbon dioxide poses no direct health risk at ambient levels (350–500 parts per million) or modestly elevated concentrations. It is neither flammable nor explosive — in fact, it is used in fire extinguishers as it displaces the oxygen the fire needs to burn. However, since CO₂ is denser than air, it can collect in higher concentrations in confined, low-level spaces and under these conditions it can cause asphyxiation (oxygen deficiency).

The safe storage of injected CO₂ involves the detailed characterisation of a suitable storage site that is also well managed. Properly designed sites will have a couple of injection zones that can receive and store large quantities of CO₂, will be overlain by appropriate caprocks and will not be situated in areas that have a high incidence of seismicity. Fortunately, in South Africa there are few areas where seismicity would be a significant concern, allowing for deployment across the widest range of prospective basins in the country. Geophysical surveys should also be undertaken to assess the deep structures of storage basins for faults that may allow injected CO₂ to migrate out of the target injection zone. Seismic surveys are but one of many aspects of a comprehensive pre-injection site evaluation that would need to be performed at each candidate CO₂ storage site.

Measuring, monitoring and verification (MMV) systems are required to guarantee that injected CO₂ stays in the target zone. Various commercially available technologies are available to monitor the different aspects of CO₂ storage. Large-scale CCS operations may, however, require the development of a significantly more robust and accurate set of MMV technologies to detect potential leaks long before they pose a danger to any drinking-water reservoirs or surface ecosystems.

The Intergovernmental Panel on Climate Change (IPCC) Special Report on carbon capture and storage expressed its expert opinion as follows: "With appropriate site selection informed by available subsurface information, a monitoring program to detect problems, a regulatory system, and the appropriate use of remediation methods to stop or control CO₂ releases if they arise, the local health, safety and environment risks of geological storage would be comparable to risks of current activities such as natural gas storage, enhanced oil recovery and deep underground disposal of acid gas."
Categorisation of storage potential assessments
(using the Techno-Economic Resource-Reserve Pyramid)

Two pyramids (Figure 2.5) are generally in use to illustrate the assessment scale and certainty with which storage capacity estimations can be made, in much the same way as the deposits of other energy and mineral commodities such as oil, gas, coal, gold, etc. are classified\(^8\)\(^9\)\(^10\).

The selection of a suitable site for the storage of significant volumes of CO\(_2\) requires mainly geological evaluation on progressively more and more detailed scales\(^1\). The different levels of site assessment that can be undertaken range from an initial regional screening to highly detailed site-specific characterisation. Each level of detail progressively reduces uncertainty, but typically, also results in a decrease of the calculated storage volume. In addition, each level of detail in site selection requires greater effort, and increasing amounts and types of data, time and expenditure (Figure 2.5).

The following levels of estimation are nested within the resource-reserve pyramid\(^1\):

1. **Theoretical Storage Capacity** encompasses the total resource. It depicts the absolute physical limit of what the geological system can accept by assuming that the system's entire capacity to store CO\(_2\), (in pore space, or dissolved at maximum saturation in formation fluids, or adsorbed at 100% saturation in the entire coal mass) is accessible and fully utilised.

2. **Effective Storage Capacity** represents the subset of the theoretical capacity and is obtained by considering that part of the theoretical
storage capacity that can be physically accessed and which meets a range of geological and engineering criteria.

3. **Practical Storage Capacity** is the subset of the effective storage capacity that is obtained by considering technical, legal and regulatory, infrastructure and general economic criteria that allow CO₂ geological storage. The Practical Storage Capacity corresponds to the term 'reserves' used in the energy and mining industries.

4. **Matched Storage Capacity** is the subset of the practical storage capacity that is obtained by detailed matching of the CO₂ streams from an individual or collective point sources with geological storage sites that are adequate in terms of capacity, injectivity and supply rate, to contain those CO₂ streams. This capacity is depicted at the top of the resource pyramid and corresponds to the term 'proven marketable reserves' used by the mining industry.

Due to the scope of this Atlas and quality of available data, the levels of Practical and Matched Capacity assessments (or Contingent and Operational Storage Capacities, Figure 2.5) have not been attempted.

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Figure 2.5 — Integrated scales of assessment of storage capacity certainty for geological storage of CO₂, (Techno-Economic Resource-Reserve Pyramid). The storage volume level assigned to the scale of characterisation represents the maximum likely assessment level achievable, given the likely availability of data, (a) and (b).
Figure 3.1 — Simplified onshore geology of South Africa, showing the large area covered by sedimentary basins. For further clarity the main onshore and offshore basins assessed for CO$_2$ storage in this Atlas are highlighted in Figures 3.4 and 3.12 respectively.
Part Three

Geological Storage Capacities

Potential and estimated carbon dioxide storage capacities of geological formations in South Africa

The varied geological history of South Africa spans a period of more than 3 600 Ma (million years) and is not only responsible for the mineral wealth of the country\(^1\), but also for its unique geographical regions, landscapes and places of great scenic beauty\(^2\). South Africa is well endowed with sedimentary basins that were formed from as long ago as the Archaean (>2 500 Ma) to the most recent period. For descriptive purposes, the sedimentary fill of each basin is grouped into units or supergroups (Figure 3.1)\(^3\). Sedimentary basins cover most of the land surface and contain more than 80%, in value, of the economic mining commodities in South Africa\(^4\). Unfortunately, in the majority of these basins the rocks are metamorphosed\(^5\) and the basins are structurally complex\(^6\), making them unsuitable for the storage of CO\(_2\). These rocks have no primary porosities, only secondary porosities where they have been faulted and fractured. This deformation of the rocks could negatively affect the containment of injected CO\(_2\) and make the modelling of CO\(_2\) movement in the potential reservoirs very complex, with a high level of uncertainty (Figure 3.2). It will also be very difficult to prove containment security of the injected CO\(_2\). The possibility that the storage of CO\(_2\) could compromise the utilisation of high-value mineral deposits, associated with most of these basins, also impacts negatively on their suitability as storage sites. It is likely that only the basins of Late Palaeozoic age (Karoo Basin) and Late Mesozoic age could be viable for the storage of CO\(_2\). These basins are relatively young, largely unmetamorphosed and undeformed, and their stratigraphy and depositional histories are well understood (Figure 3.3).
Figure 3.2 — Folded and faulted quartzites (metamorphosed sandstones) of the Table Mountain Group (Seweweekspoort).

Figure 3.3 — Thick lenticular sandstones (light coloured) interbedded and enclosed within a fine-grained mudrock (dark coloured); an ideal configuration for the storage of CO₂ (Karoo Supergroup at Graaff-Reinet).
Karoo Basin (Karoo Supergroup)

The Karoo Supergroup fills the largest sedimentary basin in South Africa and is well known for its fossil wealth\(^1\). It underlies almost 60% of the land surface (~700,000 km\(^2\)) and attains a total cumulative thickness of about 12 km in the southern part of the basin\(^2\). The bulk of the Karoo strata in South Africa occurs in the main basin, but significant deposits are also present in the smaller Springbok Flats, Ellisras, Tshipise and Tuli Basins to the north of the main basin, while an easterly dipping monocline has resulted in the preservation of a narrow strip of Karoo rocks in a linear belt along the eastern margin of South Africa (Figures 3.4 and 3.5).

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Figure 3.4 — Location of the Karoo Supergroup in South Africa and adjacent territories\(^3\). The Durban-Lebombo Belt extends from north of Durban and forms the Lebombo Mountain Range.
Figure 3.5 — Schematic section across the Main Karoo Basin and the Durban-Lebombo Belt (see Figure 3.4 for location of section).
It is likely that only the basins of Late Palaeozoic age (Karoo Basin) and Late Mesozoic age could be viable for the storage of CO$_2$.

The Karoo Basin is largely underlain by a stable floor, and deformation of the basin is only present along its southern margin where it is bound by a fold-thrust belt (the Cape Fold Belt). Deposition of the sediments commenced during the Late Carboniferous Period and terminated in the Early Jurassic Period with the outpouring of basalts of the Drakensberg and Lebombo Groups. A variety of sediments were deposited in the Karoo Basin, initially comprising glacial deposits at the base, followed by basin plain and shelf mudstones, turbiditic sandstones, deltaic and fluvial sandstones and mudstones, finally terminating with aeolian sandstone deposits (Figure 3.6). The whole sedimentary package of the Karoo Supergroup was intruded during the Jurassic Period by dolerite, an igneous rock that was emplaced as horizontal sills and vertical dykes (Figures 3.7, 3.8, 3.9 and 3.10).

Figure 3.6 — Depositional environments of the Karoo Supergroup. Note that the non-aeolian units above the Katberg Formation (i.e. the Burgendrop, Molteno and Elliot Formations that are not shown) represent further episodes of both braided and meandering fluvial conditions, while deposition of the Dyka Group (glacial) and Prince Albert, Whitehill and Collingham Formations (moderately deep water) preceded the main sediment influx from the south.
Figure 3.7 — An example of a dolerite dyke cross-cutting horizontal beds of red mudstone and (lighter coloured) sandstone of the Elliot Formation, Barkly Pass, Eastern Cape Province. Note the slight displacement of the sandstone and mudstone layers on either side of the dyke. The dyke, in all likelihood, served as a feeder channel to the volcanic extrusions of basalt that occur close by, but at a stratigraphically higher elevation. The dyke is terminated at the top of the road cutting by the current erosion surface.
Sandstones in the central part of the Main Karoo Basin and along the Durban-Lebombo monocline, especially the Vryheid Formation underlying the areas indicated in yellow in Figure 3.12, occur at depths suitable for CO₂ storage and are accompanied by cap and lateral seals. Unfortunately, mainly owing to a high degree of diagenesis, resulting from sedimentary burial, and igneous and volcanic activity, the porosities and permeabilities of the sandstones are very low — probably too low for effective and economic storage and injection. The presence of dolerite sills and dykes also causes compartmentalisation (Figure 3.8) and precludes geophysical techniques to accurately locate suitable reservoirs or to monitor the movement of CO₂ after injection. Consequently, no saline formation storage calculations were undertaken for the Karoo Basin. On account of the basin’s large size, onshore position and its proximity to major CO₂ point sources, research should, nevertheless, continue on low porosity and permeability injection techniques, as well as on the suitability of CO₂ storage in the uppermost sandstones of the Molteno and Clarens Formations for which little porosity and permeability data are currently available.

In the northern and eastern parts of the Main Karoo Basin and also in the subsidiary basins to the north and east, significant coal deposits are economically exploited (Figure 3.11). They provide the main source of energy for South Africa and support a large export industry of mainly bituminous, thermal-grade coal with relatively low sulphur contents. The presence of these extensive coal deposits has helped stimulate both the mining and manufacturing industries in South Africa, has enabled the country to become the world leader in coal-to-liquid technology, and has enabled the production of some of the lowest-cost electricity in the world.
Figure 3.9 — Remnants of a dolerite sill capping the crest of a mountain made up of Adelaide Subgroup mudstones with minor sandstone lenses, south of Graaff-Reinet.
Figure 3.10 — Distribution of Karoo basalt in South Africa, Lesotho and Swaziland and the dolerite-sediment ratio of the Main Karoo Basin. The higher the dolerite-sediment ratio, the greater the disruption of storage formation seal pairs becomes.
South Africa currently does not have a mature coalbed methane industry to support CO$_2$ storage.

Some of the deeper, unmineable coal seams (defined as seams deeper than 300 m) could theoretically support a coalbed methane (CBM) industry, which, combined with CO$_2$-enhanced coalbed methane recovery, may provide an opportunity for CO$_2$ storage. However, South Africa does not currently have a mature CBM industry, despite a number of companies that have been doing ongoing prospecting and research on CBM potential. Presently a methane volume of about 0.14–0.28 trillion m$^3$ is postulated for South Africa$^{11}$ from which an estimated storage potential for CO$_2$, of between 277–1 386 million tonnes can be extrapolated. This potential storage capacity is highly dispersed amongst smaller storage basins/areas (Figure 3.11).

The relatively small, highly disaggregated storage potential, in combination with an immature CBM industry, possible unfavourable coal properties and controversy over the definition of 'unmineable' all have a negative effect on the coalbed storage potential of the coalfields of the Karoo Basin.

Figure 3.11 — Estimated CO$_2$ storage capacities for the different coalfields and distribution of deep coalbeds in South Africa.
Figure 3.12 — Possible deep saline formation storage opportunities in the Karoo Basin of South Africa. Note also the main offshore basins that have been evaluated for their CO₂ storage potential.
Gondwana was a supercontinent consisting of South America, Africa, India, Australia and Antarctica. It existed around 300 to 200 million years ago. These continents are now widely separated. Gondwana began to break up in the mid-Jurassic (about 167 million years ago), at which time South Africa’s offshore sedimentary basins started to form.

**Orange, Outeniqua and Durban/Zululand Basins**

Since the break-up of Gondwana into the African and South American plates, Jurassic and younger basins have developed both on land and mainly offshore around the coast of South Africa (Figure 3.13). At this stage the Falkland Islands lay off the southeast coast of South Africa, and the break-up started along the eastern margin of Africa, with Madagascar and Antarctica beginning to move away during the Middle Jurassic Period (Figure 3.13). This formed a narrow passive margin with very limited sediment deposits. It was only in the north that an appreciable sedimentary package was deposited in the Zululand and Durban Basins.

During the Early to Mid-Cretaceous a complex series of microplates, including the Falkland Plateau, gradually moved west-southwestwards past the southern coast of Africa, creating important dextral shearing of the South African margin. This created the Outeniqua Basin as a series of oblique or en échelon sub-basins, each of which comprises a complex of rift half-grabens, overlain by a variable thickness of drift sediments. These half-grabens, with tilted sediments, may be regarded as failed rifts, with the oldest in the east and the youngest in the west. The rift phase on the south coast ended in the Lower Valanginian (rift-onset unconformity, 1At1, cf Figure 3.14), but was followed by at least three phases of inversion related to continued strike-slip movement. This ended in the mid-Albian (14At1), with the final separation of the Falkland Plateau from Africa. The transitional rift-drift phase was followed by the development of a true passive margin (Figure 3.15). The Lower Valanginian drift-onset unconformity (1At1) on the south coast is contemporaneous with the earliest oceanic crust in the South Atlantic.23,24

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**Figure 3.13** — Pre-break-up distribution of Mesozoic rift basins in southwest Gondwana. The Orange, Outeniqua and Durban/Zululand Basins along the South African coast are indicated.25
Figure 3.14 — Sequence chronostratigraphic frameworks of the Orange Basin and Bredasdorp Sub-basin of the Outeniqua Basin, illustrating the main tectonic and depositional events in these offshore Mesozoic basins.
Figure 3.15 — Schematic section across the Bredasdorp Sub-basin (Outeniqua Basin); sandstones that can potentially act as saline storage reservoirs are indicated by stipple patterns."
Figure 3.16 — Producing and depleted oil and gas fields of South Africa, in the offshore Outeniqua Basin. Depth contours are at the mid-Albian horizon (1A\(\text{At}1\))
Although the storage capacity of the oil and gas fields in the Outeniqua Basin is relatively small, together with the large amount of geological information already available, these could represent an early economic opportunity for storage.

The Orange Basin was initiated as a series of isolated and linked north–south-trending grabens during the Lower Cretaceous. The drift-onset unconformity here is dated as Hauterivian (6At1), somewhat younger than in the Outeniqua Basin. A rift-drift transitional phase in the Orange Basin occurred until the Early Aptian (13At1). Later Cretaceous and Tertiary sedimentation took place in a marine passive-margin setting.

The rift sequences generally consist of continental fluvial red beds, with subordinate grey lacustrine sediments and volcanic material in places, overlain by shallow-marine and deltaic sediments. Rapid deepening of the basins occurred after onset of drift, with the lower part characterised by deep-marine basin-floor claystones and turbidites, which grade upwards into shelf sediments deposited during the upper Cretaceous and Tertiary.

South Africa’s only producing oil and gas fields are situated in one of these offshore basins, the Outeniqua Basin (Figure 3.16). South Africa’s oil and gas fields are relatively small and only an estimated 62 million tonnes of CO₂ could currently be stored in depleted and near-depleted oil and gas fields along the south coast or Outeniqua Basin. In addition, known gas and oil reserves (in both the Orange and Outeniqua Basins) could have an estimated storage potential for a further 15 million tonnes of CO₂ after depletion. Although the capacity is small, together with the substantial amount of geological data available, these could represent an early and economic opportunity for storage, since enhanced oil and gas recovery may be possible.

In comparison, the storage capacity of deep saline formations in the offshore Mesozoic basins (Orange, Outeniqua, Durban and Zululand) is projected to be very large. Unlike oil and gas reservoirs, no structural traps are required for the storage of CO₂ only top and lateral seals, which are present in the form of impermeable mudstones. Fortunately, in some of the offshore basins multiple reservoir/seal pairs are also present. It is estimated that in the offshore basins of South Africa (Figure 3.17) the expected CO₂ storage capacity is about 148 000 million tonnes, of which about 1 800 Mt is associated with closures and traps that may well contain oil and/or gas.

In the larger Late Mesozoic onshore basins (Zululand and Algoa Basins) deep saline formations are also present and an estimated storage capacity of about 500 million tonnes of CO₂ is estimated for each (Figure 3.17). Lateral seals, especially for the Zululand Basin, must still be demonstrated and more research and data are necessary to confirm these estimates.

Currently, the Outeniqua Basin appears the most valuable of the offshore basins for storage because of the existing infrastructure and the availability of geological data. However, major obstacles in the development of these storage sites are their offshore position, the lack of detailed data in some areas, the depth of the reservoirs and the distance to the main CO₂ point sources.
Figure 3.17 — Possible deep saline formation storage opportunities onshore and offshore in Mesozoic basins along the coast of South Africa and for the deep coalfields of the Karoo Basin. Storage capacity of the basins and coalfields are indicated by round symbols (black) and data confidence by purple figures (Table 3.1).
Confidence indicator for capacity estimates

The Carbon Sequestration Atlas of the United States and Canada uses a combination of the availability of data and the subsurface heterogeneity to construct a simple rubric (Table 3.1). This provides a relative index to estimate the level of confidence (1 — low to 9 — high) associated with the calculated storage capacity. It was attempted to apply this rubric to data estimates in the South African Storage Atlas.

For the offshore basins, i.e. Outeniqua, Orange and Durban/Zululand Basins, it is clear that the borehole density (Figure 3.12) is low. This is even true for relatively high prospective areas, such as the Bredasdorp Sub-basin (less than 1 borehole/160 km²), whereas its seismic line spacing ranges from low to high. At its best, the subsurface heterogeneity is low, which gives a medium (5) confidence level for both data availability and the capacity estimate for the best explored parts of the sub-basin. For the Outeniqua Basin as a whole, however, a confidence level 3 is suggested (cf/Table 3.1 and Figure 3.17). A similar lack of data also results in a low (1) confidence level in the capacity estimated for the Durban/Zululand Basin.

For the Karoo Basin the borehole and seismic survey densities are low (1) which, together with an intermediate subsurface heterogeneity, yields a capacity estimate confidence level of 3.

The confidence indicator for the onshore Mesozoic basins is generally better, but data availability in some critical areas is still lacking, resulting in a medium (5) confidence level for the capacity estimates associated with these basins.

Calculations of storage capacities were done according to the standard methods as recommended by the Carbon Sequestration Leadership Forum (CSLF) in 2007 and the potential storage capacity estimates are summarised in Figure 3.17.

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<thead>
<tr>
<th>Subsurface heterogeneity</th>
<th>Data density</th>
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<tr>
<td>High</td>
<td>5</td>
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<tr>
<td>Moderate</td>
<td>7</td>
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<tr>
<td>Low</td>
<td>9</td>
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<td></td>
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<tr>
<td>borehole density</td>
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<td>borehole density</td>
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Table 3.1 — Relative confidence indicator of the data and subsequently also of the estimated capacity calculations.
Summary

The estimated capacity of geological storage in South Africa is around 150 Gt (150 000 Mt) of CO$_2$. The largest storage volume (~98% of the total storage potential of South Africa) is present in the Mesozoic basins along the coast of South Africa (Figure 3.17). The storage potential lies mainly in the capacity of saline formations associated with the oil- and gas-bearing sequences in the Outeniqua, Orange and Durban/Zululand Basins. The estimated capacities are: ~48 Gt for the Outeniqua Basin, ~56 Gt for the Orange Basin and ~42 Gt for the Durban/Zululand Basin. Less than 2% of the estimated storage capacity of South Africa occurs onshore: ~0.46 Gt for the onshore Zululand Basin, ~0.40 Gt for the onshore Algoa Basin and ~1.2 Gt for the coalfields of South Africa.

There is some highly disaggregated potential for the storage of CO$_2$ associated with ECBM from deep unmineable coal seams, should a CBM industry develop in South Africa. As discussed earlier, the definition of 'unmineable' is based on technoeconomics and the future mining of these coalbeds must also be taken into consideration. The potential for underground coal gasification (UCG) would effectively negate the possibility of storage through ECBM, but UCG may itself create new storage opportunities.

The two larger onshore Mesozoic basins (Zululand and Algoa) are likely to contain viable saline formations, but the effectiveness of caprocks and lateral seals must still be determined.

For the offshore areas the data certainty is somewhat better because of the availability of significantly more information in the form of seismic surveys and drill core resulting from oil and gas exploration activities. The quality of data for the Outeniqua Basin varies significantly for its four sub-basins, and moderate to low confidence levels have been expressed.

The offshore oil and gas fields can be used for storage, including the possibility of EOR and EGR. The basins hosting these fields also have a large saline formation storage potential. The costs and logistics, however, that result from their offshore position, depth, lack of detailed information and distance to major (onshore) CO$_2$ point sources will have to be considered.
By definition, this Atlas has been a literature study of all available information on the subject, which has mainly come from the archives of the Council for Geoscience and the Petroleum Agency SA. Most of this information has now been collated and is represented here and in the companion document of the Atlas, Technical Report on Geological Storage of Carbon Dioxide in South Africa (2010). Additional new information to refine the geological storage capacities further would require more basin-specific and site-specific information. The geological and engineering data needs for improving the capacity estimates are specific and well described in the literature (e.g. CO2CRC, 2008).

This Atlas has significantly progressed beyond previous attempts to estimate South Africa’s geological storage capacity and has clarified, for decision-makers, where the real potential exists, as well as offering smaller and maybe early storage opportunities on which the technology can be demonstrated for South Africa.

Carbon capture and storage in South Africa is somewhat of a dilemma for policy-makers. CCS may ultimately play a limited role in meeting South Africa’s climate change mitigation goal — restricted to small-scale niche applications that are close to point sources. Alternatively, carbon capture and storage could play a huge role in meeting South Africa’s goals for both climate change mitigation and energy security — with the large-scale movement of either the coal or the CO₂ emissions to the areas where storage potential has been identified. The resolution of the dilemma is the goal of the CCS programme in South Africa, of which this Atlas forms a large component.

Investment decisions are likely to follow an iterative process between estimating the costs for matching sources to potential sinks and obtaining further geological information, as well as investing in alternative mitigation options. This last consideration really only applies in the shorter term, if one accepts the assertion that all types of mitigation will be required in order to address both climate change mitigation and energy security. Overall, long time frames are required to characterise potential storage reservoirs, develop the necessary skills and technology base, and to consult with the public. This Atlas is a key component of the programme that is intended to develop a full-scale CCS deployment beyond 2025.

The way forward to enhance the information gathered for this Atlas probably lies in the formation of partnerships between the major stakeholders in industry and Government, and the securing of sufficient funding. The demand on resources to achieve the macro-scale storage solutions should not, however, distract from undertaking smaller-scale research and demonstration, given the long time frames and the capacity building that would be required.
Appendix
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    CSLF (Carbon Sequestration Leadership Forum), 2008. Comparison between methodologies recommended for estimation of CO₂ storage capacity in geological media by the CSLF Task Force on CO₂ storage

11 Wilson and Anhaeusser, 1998

12 Johnson et al., 2006a

13 Keyser, 2006

14 Martini et al., 2000

15 Saggerson and Turner, 1992; 1995

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17 MacRae, 1999

18 Johnson et al., 2006b
Endnotes/References


19 Winter and Venter, 1970

20 Planke, 2005

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22 Methane to Markets, 2008

23 Petroleum Agency SA, 2008

24 Broad et al., 2006

25 SOEKOR, 1994

26 DOE, 2007

27 CSLF, 2007
aeolian  relating to wind-driven processes, e.g. wind-blown sand or dust
Albian the youngest or uppermost subdivision of the Early or Lower Cretaceous Period. Its approximate time range is 112 to 97 Ma
aquifer a porous rock, such as sandstone, that carries water. Situated at increasingly greater depths the salinity of the aquifer water can increase to levels where it becomes unsuitable for human consumption. Such formations are referred to as deep saline formations
Archaean the oldest eon of the Precambrian, ranging in age from the formation of the earth at ~4 600 Ma to 2 500 Ma
basalt a fine-grained, dark, basic, igneous rock of volcanic origin
Carboniferous the fifth period in the Palaeozoic Era between the Devonian and Permian Periods, ranging from approximately 360 Ma to 290 Ma
coal rank the stage coal has reached on the coalification path pertaining to or characterised by a delta, e.g. ‘deltaic sedimentation’
deltaic dextral shear the sense of movement across a displacement boundary in which the side opposite the observer moves to the right
diagenesis the sum of the physical, chemical and biological changes that take place in sediments as they become consolidated into rocks, including compaction and cementation, but excluding weathering and metamorphic changes
dolerite a dark, medium-grained, igneous rock typically occurring in dykes and sills and having the same chemical composition and origin in the earth’s crust as basalt
dyke a minor, sheet-like, near-vertical, igneous intrusion cutting across horizontal to gently dipping planar structures in the country (native) rock
en échelon a set of short, linear features that overlap or are staggered in a line that runs obliquely to the strike of the individual features
faulting the process of fracturing and displacement that produces a fault
of or pertaining to a river or stream
fluvial fold-thrust belt a belt of discrete thrust faults and folds along a foreland margin
geochemistry the study of the chemistry of the earth’s constituents
geophysics the application of the methods and techniques of physics to the study of the earth and the processes affecting it
Gondwana a southern supercontinent embracing South America, Africa, India, Madagascar, Australia and Antarctica which probably formed over 2 000 Ma ago and began to split some 180 Ma ago
### Glossary

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
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<tbody>
<tr>
<td>graben</td>
<td>a valley formed by the subsidence of a fault block between normal faults</td>
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<tr>
<td>Group</td>
<td>a stratigraphic term used for a grouping of formations</td>
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<tr>
<td>half graben</td>
<td>a dropped zone comprising a dipping fault on one side of a block of tilted strata</td>
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<tr>
<td>Hauterivian</td>
<td>a stage of the Cretaceous Period, extending from 135 to 131 Ma</td>
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<tr>
<td>igneous rock</td>
<td>a rock that has solidified from magma (molten rock)</td>
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<tr>
<td>jointing</td>
<td>fracturing on which any displacement is too small to be visible to the unaided eye</td>
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<tr>
<td>Jurassic</td>
<td>the middle period of the Mesozoic era, ranging from 208 to 145.6 Ma</td>
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<tr>
<td>lacustrine</td>
<td>referring to a lake</td>
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<tr>
<td>magmatism</td>
<td>the formation of igneous rock from magma</td>
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<tr>
<td>Mesozoic</td>
<td>an era comprising the Triassic, Jurassic and Cretaceous Periods, 245 to 65 Ma</td>
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<tr>
<td>metamorphism</td>
<td>the processes by which rocks are changed by the solid-state application of heat, pressure and fluids, but excluding weathering and diageneisis</td>
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<tr>
<td>methane</td>
<td>a colourless, odourless, flammable gas and the main constituent of natural gas (used as a fuel); the lightest component of crude oil and also an important component of marsh gas formed by the decomposition of organic material in the absence of air</td>
</tr>
<tr>
<td>microplate</td>
<td>a small tectonic plate with identifiable margins, which may subsequently become a displaced terrane</td>
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<tr>
<td>monocline</td>
<td>an asymmetric fold with one limb dipping at a lower angle than the other</td>
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<tr>
<td>passive margin</td>
<td>the transition between oceanic and continental crust, which is not tectonically active</td>
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<tr>
<td>permeability</td>
<td>the property or capacity of a porous rock, sediment or soil for transmitting a fluid</td>
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<tr>
<td>porosity</td>
<td>a measure of the void spaces in a material, expressed as a fraction of the volume of voids over the total volume, between 0-1, or a percentage between 1-100 percent</td>
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<tr>
<td>reservoir</td>
<td>a subsurface rock containing commercially exploitable quantities of oil and/or gas</td>
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<tr>
<td>rift</td>
<td>a place where the earth's crust is being pulled apart</td>
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<tr>
<td>sandstone</td>
<td>a sedimentary rock composed mainly of sand-sized grains</td>
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<tr>
<td>sedimentary basin</td>
<td>any geographical feature exhibiting subsidence and consequent infilling by sedimentation</td>
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<tr>
<td>seismicity</td>
<td>the distribution of earthquake-induced earth movements in time, location, magnitude and depth</td>
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<tr>
<td>seismology</td>
<td>the study of earthquakes, and of the structure of the earth, by both natural and artificially generated seismic waves</td>
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<tr>
<td>shale</td>
<td>a fine-grained, clastic, sedimentary rock composed of mud, which is a mixture of clay minerals and</td>
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sill
a concordant, tabular or sheet-like igneous body from a few centimetres to hundreds of metres thick
subcritical state
a substance at a temperature and pressure below its critical point (i.e. the point at which the gas, liquid and solid phases of a substance are in equilibrium)
supercritical state
a substance at a temperature and pressure above its critical point. It shows properties of both liquids and gases, expanding to fill a container like a gas, but with the density of a liquid
Supergroup
the largest lithostratigraphic subdivision, comprising a series of groups, or groups and formations
tectonism
the production of geological structures by deformation (an application of force to change the geometry)
Tertiary
a period of the Cenozoic Era comprising the Palaeocene to Plioene Epochs, 65 to 1.64 Ma
turbiditic
sediment driven by gravity, with the potential of moving down or even up a slope
unconformity
a break in the stratigraphic record which represents a period of no sediment deposition or erosion
Valanginian
an age or stage of the Early or Lower Cretaceous. It spans the interval between 140.7 and 135 Ma
Further reading


Further reading


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Contributors

PetroSA
The Petroleum, Oil and Gas Corporation of South Africa owns, operates and manages South Africa's commercial assets in the petroleum industry.
151 Frans Conradie Drive
Parow
tel: +27 (0)21929 3000
www.petrosa.co.za

Sasol
Sasol is a global petrochemical group involved in mining, energy, chemicals and synguels.
Baker Square East
33 Baker Street
Rosebank
tel: +27 (0)11441 3111
www.sasol.co.za

SANERI
The South African National Energy Research Institute is a public entity entrusted with the coordination and undertaking of public-interest energy research, development and demonstration.
First Floor, CEF House
Block C, Upper Grayston Office Park
152 Ann Crescent, Strathaven
Sandton
tel: +27 (0)10 201 4700
www.saneri.org.za

Petroleum Agency SA
The Petroleum Agency SA promotes exploration for onshore and offshore oil and gas resources and their optimal development on behalf of the Government.
Tygerpoort Building
7 Mispel Street
Bellville
tel: +27 (0)21 938 3500
www.petroleumagency.co.za

Eskom
Eskom is South Africa's electricity utility and the largest producer of electricity in Africa.
Megawatt Park
Maxwell Drive
Sunninghill
Sandton
tel: +27 (0)11 800 8111
www.eskom.co.za

Anglo American
The Anglo Coal Division is a major role-player in the coal-mining industry.
Second Floor
45 Main Street
Marshalltown
Johannesburg
tel: +27 (0)11 638 9111
www.angloamerican.co.uk

Council for Geoscience
The Council for Geoscience undertakes geoscientific research and provides geoscientific services to a variety of clients, including the Government.
280 Pretoria Street
Silverton
Pretoria
tel: +27 (0)12 841 1911
www.geoscience.org.za