Nigerian CO_2 Storage Atlas

March 2025

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International Finance Corporation
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The creation of this Atlas was made possible by the support and cooperation of the Nigerian Upstream Petroleum Regulatory Commission (NUPRC), National Oil Spill Detection and Response Agency (NOSDRA), Nigerian Geological Survey Agency (NGSA) and Nigerian Midstream and Downstream Petroleum Regulatory Authority (NMDPRA)

Foreword

We are in the middle of a critical decade for climate action. With the temperatures rising sharply and extreme weather events disrupting communities and livelihoods, staying within the 1.5-degree Celsius warming threshold agreed at COP21 in Paris will require a total rewiring of the global economy. Renewable energy, energy efficiency and a range of new technologies, especially for hard-to-abate sectors, will all be needed for these ambitious goals. Scientific consensus recognizes carbon capture, utilization, and storage (CCUS) as one such technology with potential.

For developing countries, carbon capture can facilitate continued industrial development with lower emissions than has been historically possible. This is especially critical for hard-to-abate but vital sectors such as cement and chemical production.

Low carbon industrialization is especially important for Nigeria, with a rapidly growing population that is on track to be the third most populous country in the world by mid-century and a stated goal to reduce greenhouse gas emissions at least 20% below business-as-usual by 2030. In addition, initial assessments of Nigeria's CO_2 storage potential, including depleted oil and gas fields, are promising.

While challenges still exist for widespread deployment of this technology, especially in developing countries, IFC has a track record of creating markets for new climate technologies and financial products across a diverse range of sectors and geographies, from financing the first wind farm in Jordan to providing technical assistance to Fiji that enabled it to be the first emerging market to issue a sovereign green bond. IFC pairs sector expertise in energy and hard-to-abate sectors with deep emerging market experience and access to concessional finance.

Availability of and access to data concerning potential geological CO_2 storage locations is one of the barriers facing CCS deployment in developing countries. This Atlas, which represents a collective effort led by IFC with critical support from the Federal Government of Nigeria and numerous public and private sector stakeholders, is an important step to address the data gaps. By cataloguing prospective geological storage sites, the Nigerian CO_2 Storage Atlas helps lay the groundwork for first mover projects and, eventually, hubs and clusters that can achieve economies of scale through shared infrastructure for transport and storage.

It is our hope that this effort will be one of the first steps toward creating the enabling environment for CCS investment.

Jamie Fergusson

Director, Climate Business

Wagner Albuquerque de Almeida

Global Director, Manufacturing,
Agribusiness, and Forestry

The World Bank Carbon Capture and Storage Trust Fund (CCS TF) has responded to the request of the Government of Nigeria to provide support for the creation of the Nigeria CO_2 Storage Atlas through the generosity of its donors. Since 2009, the World Bank Group CCS TF, funded by the Government of Norway and the Government of the United Kingdom under the World Bank Energy Sector Management Assistance Program (ESMAP), has helped developing countries carry out technical, legal and regulatory assessments, map and match emission sources with geological sequestration sites along with support to pilot activities on deployment of CCS technology.

The CCS TF main objectives include strengthening capacity and knowledge building, create opportunities for developing countries to explore CCS potential, and facilitate inclusion of CCS options into developing country low-carbon growth strategies and policies.

In the years since the early days of the CCS TF the scope of support has been evolving and is currently focused on industrial applications. Globally, the pace of deployment of CCS technology accelerated backed by incentives provided by various governments in industrialized countries. There is still much work to be done globally, and especially in developing countries as the latter are critical in achieving net zero goals and meeting the objectives of the Paris Agreement.

With this Atlas, the Government of Nigeria has taken a strong step toward opening up opportunities for CCS investments. Both private and public sector stakeholders will benefit from access to data about potential geological sequestration sites, possible emissions hubs, and available transport infrastructure that may be able to be repurposed.

The analysis in this report includes inputs and validation from multiple government ministries, regulators, and private sector companies. The coordination and cooperation that made this possible is a model for other countries that are interested in pursuing CCS as part of their decarbonization plans.

Nataliya Kulichenko

Sector Leader, Sustainable Development,

Carbon Capture and Storage Program Leader

Foreword from the Nigerian Geological Survey Agency

It is with great pride and anticipation for the future that the Nigerian Geological Survey Agency (NGSA) welcomes the CO_2 Geological Storage Atlas of Nigeria. This landmark project, generously sponsored by the International Finance Corporation (IFC) in collaboration with the World Bank Carbon Capture and Storage Trust Fund (CCS TF) and expertly executed by Halliburton, marks a significant milestone in our nation's journey towards embracing Carbon Capture, Utilization, and Storage (CCUS) technologies.

The development of this comprehensive Geological Storage Atlas is a huge accomplishment for Nigeria and demonstrates our dedication to tackling the global climate change issue. It also aligns with the Federal Government of Nigeria's efforts to identify Carbon Capture, Utilization, and Storage (CCUS) as one of the critical technologies that could help Nigeria meet its climate targets and energy transition goals.

This atlas offers an essential starting point for the implementation of CCUS technologies in Nigeria by systematically locating and assessing prospective geological formations appropriate for CO_2 storage throughout the nation.

The importance of this Geological Atlas cannot be overstated. It serves as a pivotal resource for policymakers, researchers, and industry stakeholders. It will offer detailed insights into the subsurface geology of Nigeria. The data and analyses contained within this atlas will enable informed decision-making, guiding the strategic planning and implementation of CCUS projects.

CCUS technology is an essential component of our strategy to reduce greenhouse gas emissions while fostering sustainable economic growth. By capturing CO_2 emissions from industrial sources and securely storing them underground, we can significantly mitigate the environmental impact of our energy and industrial sectors. The Geological Storage Atlas is a vital tool that will help accelerate the adoption of CCUS, positioning Nigeria as a leader in innovative climate solutions.

We extend our heartfelt gratitude to the International Finance Corporation (IFC) for steering the creation of this atlas and hosting numerous workshops, the World Bank CCS Trust Fund for their invaluable support and to Halliburton for their expertise and dedication in executing this project. The collaboration and hard work of all involved parties have made this visionary project a reality.

As we move forward, the Nigerian Geological Survey Agency remains committed to advancing CCUS technologies and contributing to the global effort to combat climate change. The CO_2 Geological Storage Atlas of Nigeria is not just a document; it is a beacon of hope and a testament to our nation's dedication to a sustainable and resilient future.

Thank you.

Director General

Nigerian Geological Survey Agency (NGSA)

Contents

Executive Summary

This Atlas provides a high-level perspective on the fundamental aspects necessary for the development of a CCS industry in Nigeria. These are: a favorable regulatory environment, availability of potential transport networks, geological suitability of potential storage sites and the proximity of both transportation options and storage sites from the major emissions sources. Nigeria potentially has 10,700 gigatonnes (Gt) of prospective CO_2 storage resources. For context, meeting global climate ambitions will require about 10 Gt stored annually on a global scale by 2050. Within the Nigerian context, this means that Nigeria theoretically has sufficient CO_2 storage resources to support decarbonization of industrial sectors through carbon capture and storage.

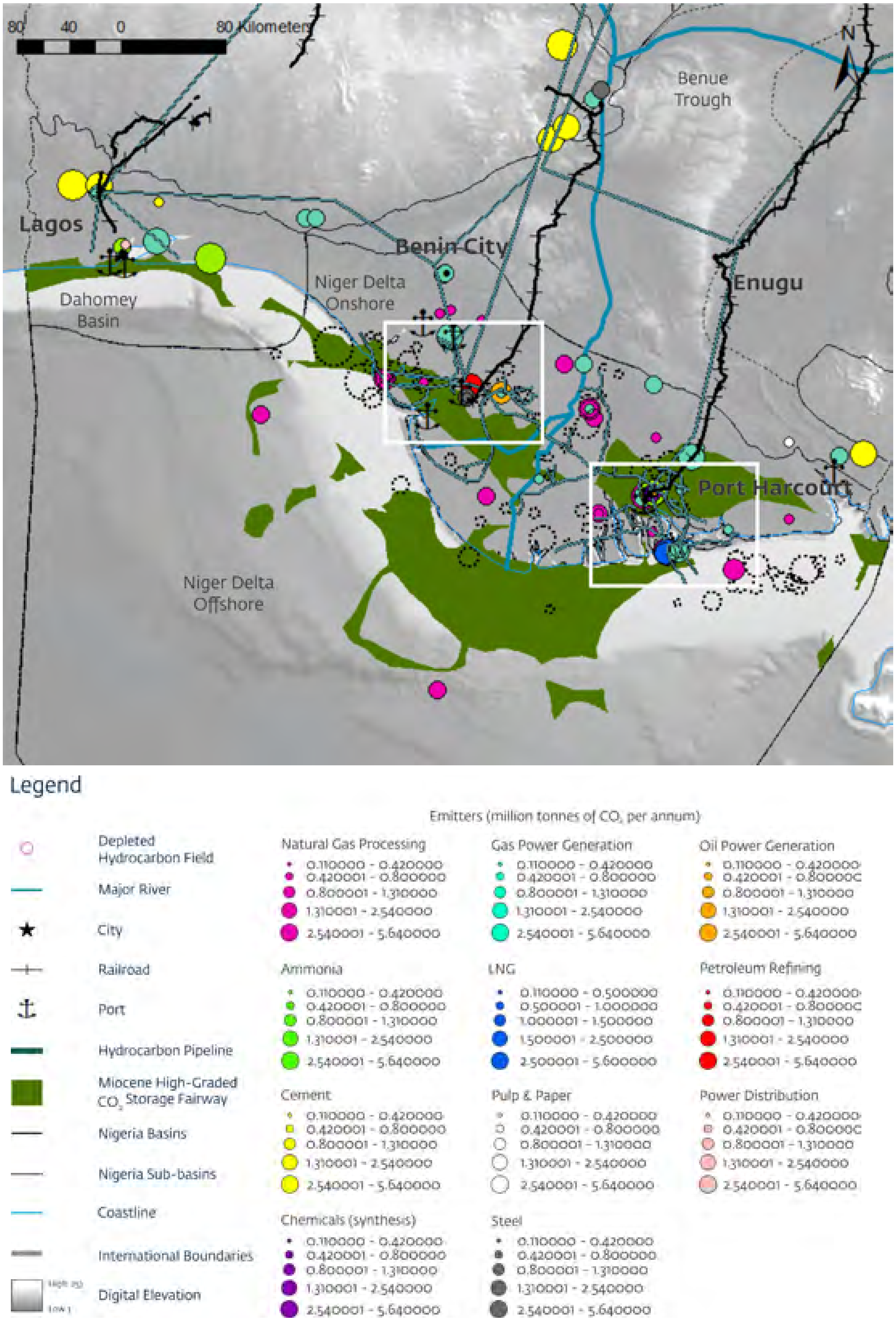
Nigeria has established a focus on climate change and environmental policy. With this motivation for decarbonisation activities, and the ability to leverage CCS experience from elsewhere across the globe, Nigeria has a good foundation for the development of policies and standards for the full CCS value chain.

The location of Nigeria's emissions sources has a high concentration of emitters from industrial sources in the Niger Delta area particularly in the regions of Lagos, Port Harcourt and around Warri and Sapele. These regions also have potential CO_2 transport networks due to the legacy oil and gas pipeline infrastructure there. In addition, there are ports and railways that could present alternative or complementary methods for moving CO_2. Analysis performed to assess the storage potential in Nigeria shows that the most suitable locations are in the Niger Delta, specifically the saline aquifers and depleted oil and gas fields within the Miocene-age formations. Figure E1 below shows the collation of the fundamental aspects necessary to initiate a CCS value chain. Locations around the industrial hubs of Port Harcourt, Lagos and Warri show favorable co-located components of the value chain (emitters, transport, and storage) which could present opportunities for future CCS development sites. Some of Nigeria's emissions source such as cement manufacturing sites, which are located in the center of the country, are far from pipelines and cannot easily leverage this potential transportation option. However, other forms of transport for CO_2 from these sites could be explored. Smaller CO_2 shipments by rail and ship are possible providing the volumes transported and distance to storage sites remain logistically and economically feasible. Transport by rail for example could transport up to 73 tonnes of liquid CO_2 up to 1600 km. Long distance transport of CO_2 by ship is already an active transport plan for the Northern Lights project in Europe, thereby presenting a case study that Nigeria could investigate to assess for potential transport along its major interior rivers.

Depleted oil and gas fields in the Niger Delta, which are centered around the areas that have been high graded as most optimal for CO_2 storage (Miocene age formations) present a favorable option to consider for CO_2 storage. These fields have a long history of hydrocarbon exploration which would give them a higher technical readiness than less explored/understood locations. The high amount of data in these fields (from drilling and other subsurface data (e.g. seismic) and modeling) would provide a greater insight into the geological suitability of the subsurface for long-term storage of CO_2.

Significant assessment (e.g. well exploration and analysis, increased data gathering, geological modeling and risk analysis) will be required in order to mature these resources into usable storage capacity. Figure E2 below shows the low, medium, and high cases for CO_2 storage resources for each basin in Nigeria that hold CO_2 storage potential. The Niger Delta storage is separated into

Figure E1. Map showing the co-location of industrial emission sources, transport networks, high graded Miocene CO_2 storage fairway areas and depleted oil and gas fields. The boxed areas near Warri and Port Harcourt show a favorable cluster of all the components for a CCS value chain. Largest circles for depleted hydrocarbon fields represent sites with resources over 100 Mt.

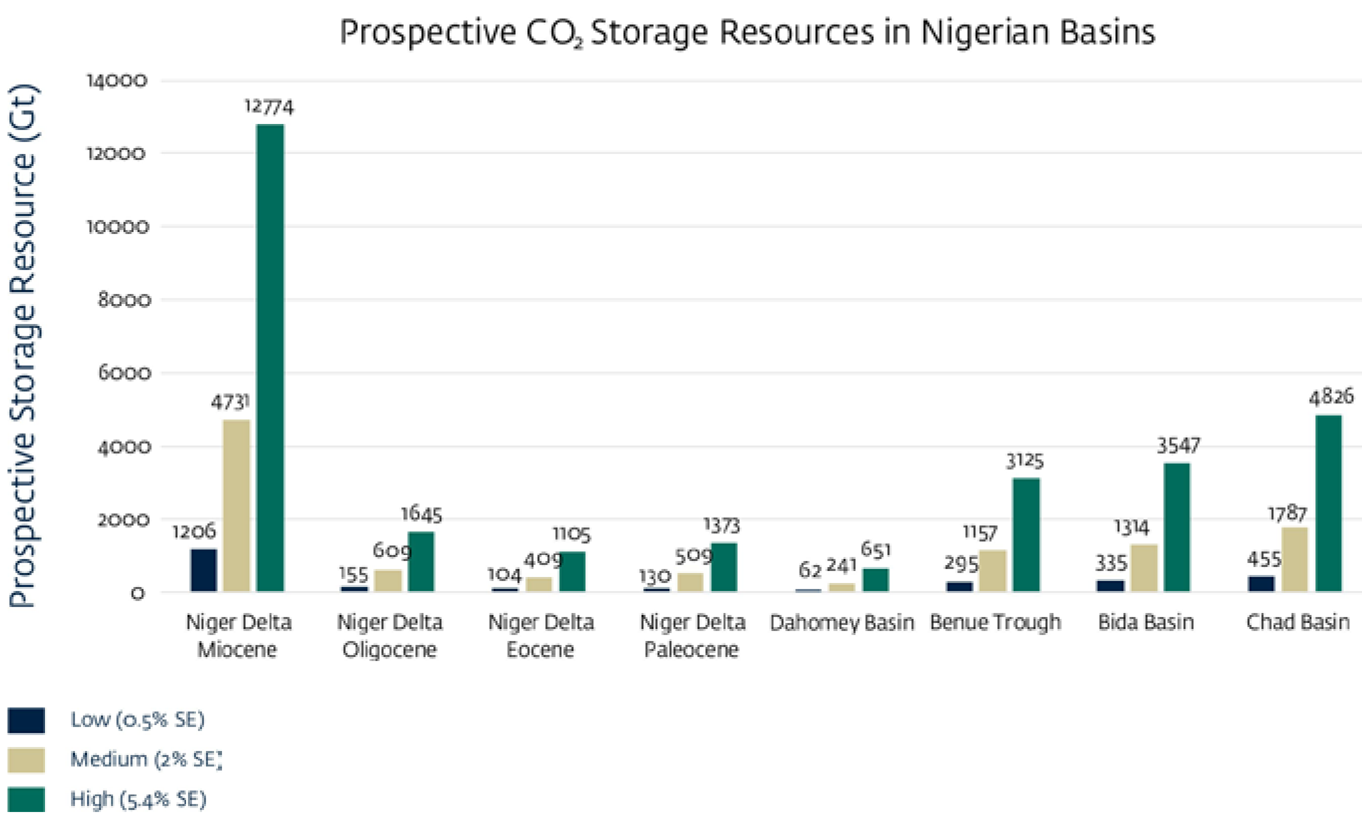


Source: Adeoti et al. 2015, Ambituuni et al. 2018, BCG, Halliburton, Humanitarian Data Exchange 2024, World Bank 2017.

geological epochs due to the large volumes in the Miocene age formations of this basin. If the storage resources are compared to Nigeria's annual emission from industrial operations of 28.13 megatonnes per annum (Mtpa) and the energy industry emissions of 38.03 (Mtpa) then it is feasible that Nigeria has sufficient CO_2 storage resources to support decarbonization of industrial sectors through carbon capture and storage.

This Atlas shows the basics of a viable CCS industry in Nigeria which is supported by both the presence of key components in the CCS value chain and a progressive focus for decarbonization from the Nigerian government. These elements combined demonstrate a positive opportunity for CCS to support Nigeria's progress towards meeting its emissions and climate goals. The scope of Nigeria's potential CO_2 resources are large (a mid-case value of 10,700 Gt) and whilst these can be expected to be refined and reduced once more rigorous analysis on sites is performed (e.g. data gathering through drilling campaigns or revaluation of existing subsurface data), the resources have good potential to remain sufficient to support decarbonisation strategies involving CCS.

Figure E2. Chart showing the prospective CO_2 storage resource volumes in Nigerian basins studied in this Atlas in Gt. A storage efficiency factor (SE) of 0.5% for low case, 2.0% for medium case and 5.4% high case is applied to the estimated resource capacity to provide high, medium and low resource estimations.



Source: Halliburton

1 Introduction

1.1 Climate Change in Nigeria

According to the World Bank, Nigeria currently has a population of 210 million (World Bank, a) and a GDP around USD 440 billion (World Bank, b) making it the most populated and largest economy in Africa, giving it both political and economic significance in the region.

The United Nations also estimates that Nigeria will become the 3rd most populous country in the world by 2050, with a population of 411 million (U.N. 2017). Therefore, Nigerian development and industrialisation is set to increase. Within Africa, Nigeria was the 4th largest greenhouse gas emitter in 2019, accounting for 12% of Africa's CO_2 emissions (World Bank, b), which translates to 0.5% of global emissions. CO_2 emissions in Nigeria have maintained a similar growth trajectory to GDP and are likely to continue to follow this path given Nigeria's rapidly growing economy, demographics and urbanization.

1.2 Nigeria's Current Climate Commitments

At the 2015 United Nations Climate Change Conference in Paris, nearly 200 countries agreed to take measures to limit global warming to two degrees Celsius (compared to the pre-industrialization level) by 2100. This includes Nigeria, which signed in 2016 (U.N. 2023). Furthermore, an aim was set to limit this to a 1.5 degrees Celsius increase above pre-industrial levels. Companies and countries around the world committed to the Paris Agreement in acknowledgment that urgent action is needed to combat climate change and its potential catastrophic consequences.

Nigeria has pledged to reduce its greenhouse gas (GHG) emissions by 20% by 2030 (Federal Ministry of Environment, 2021), compared to 'business-as-usual-levels'. However, Nigeria's energy poverty and rapidly growing population compel development and hence industrialization is a key engine to support that. Therefore, whilst Nigeria is committed to cutting CO_2 emissions it will need to ensure GHG mitigation strategies do not negatively impact industrial growth.

Nigeria's Energy Transition Plan (ETP) (Nigeria Energy Transition Plan) highlights carbon capture and storage (CCS) as a decarbonisation pathway for natural gas whilst helping to meet Nigeria's economic development and energy security goals. Furthermore, Nigeria submitted its 2050 long-term vision to the United Nations Framework Convention for Climate Change (UNFCCC) in November 2021 (Department of Climate Change, 2021) and flagged CCS as a low-carbon technology that could assist with the national effort to diversify the economy, thereby indicating CCS as a climate mitigation option for all sectors, including the industrial sector.

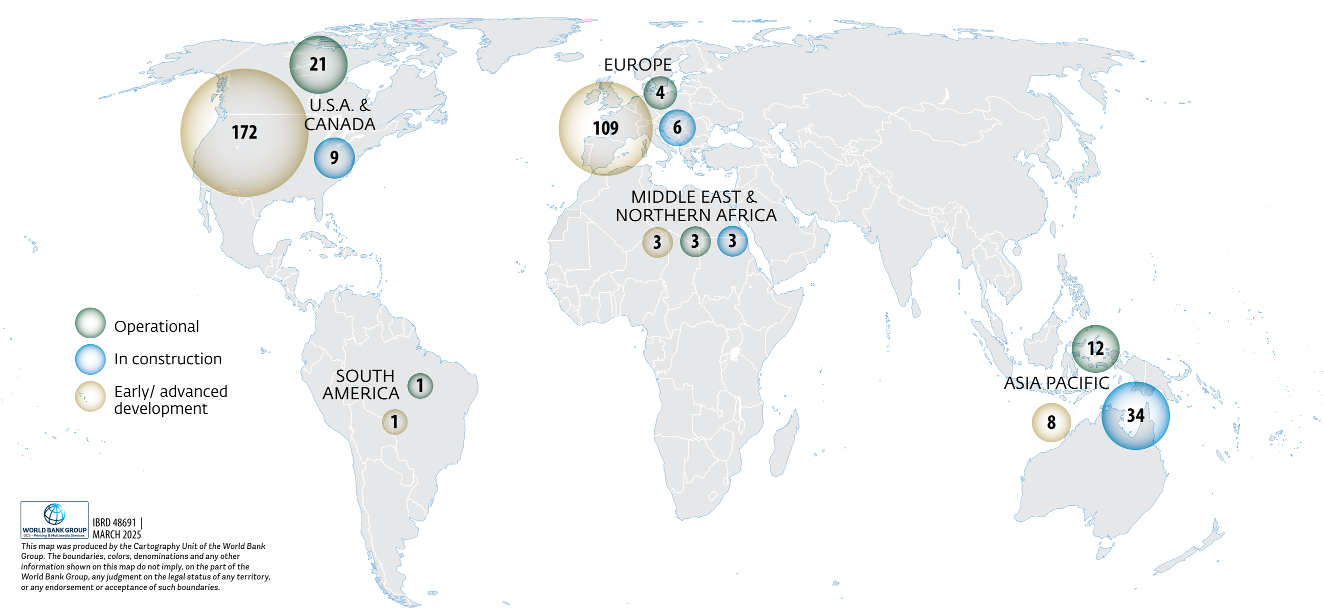
Nigeria's current climate commitments play a crucial role in advancing global aims for CO_2 reduction and mitigating climate change impacts. In addition to the nation's wide-ranging efforts to help reduce greenhouse emissions, such as its commitment to transitioning to renewable energy sources, enhancing energy efficiency and promoting sustainable land use practices, CCS can play a significant role in decarbonising Nigeria's hard-to-abate industries (Federal Ministry of Environment, 2021).

1.3 Global Status of CCS

CCS involves capturing CO_2 from stationary emitters and transporting it for long-term geological storage. While carbon capture technology has been commercially deployed for decades in the energy sector, CCS is a nascent climate mitigation lever. Current global implementation is in the region of 42-45 megatons (Mt) (GCCSI 2022) (See Box 1.1 for example projects). CCS is a capital-intensive process and, unsurprisingly, the largest concentration of CCS projects today exist in jurisdictions with strong CCS incentives, such as the USA and Europe. Asia and Australia have also made significant steps towards developing projects. Europe has made good progress with CCS projects over the past few years, with a total of 35 storage and transport networks in development, 4 operational CCS facilities and 109 in early/advanced development. (GCCSI 2023) (Figure 1.1).

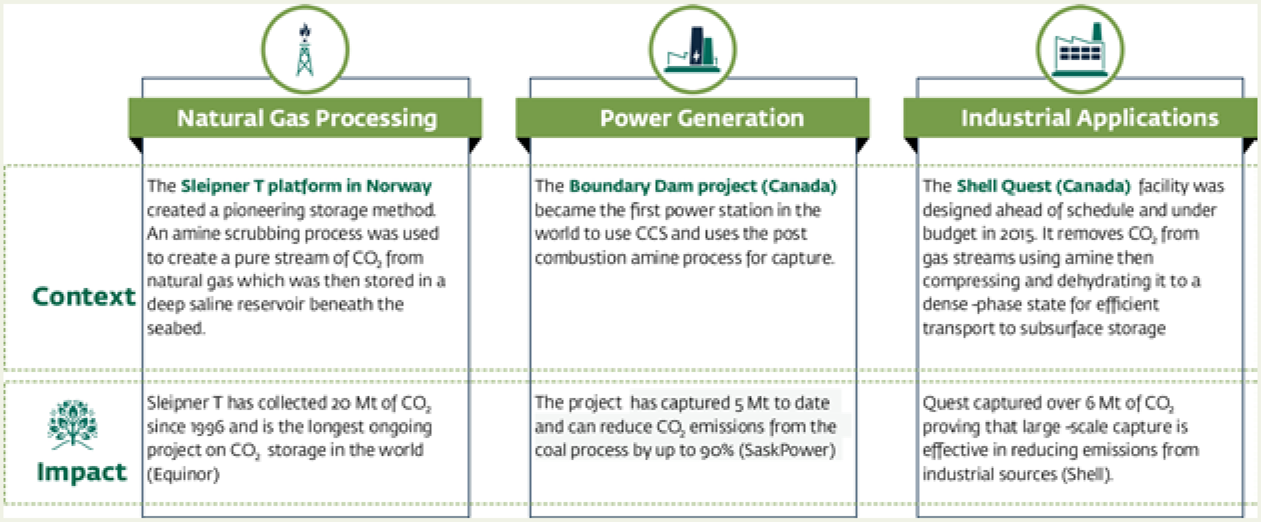
Global experience has demonstrated the importance of CO_2 source hubs for reaching commercial-scale CCS projects. These hubs are dense groups of stationary CO_2 emitters, which have access to shared transportation and storage. Hubs have become a critical aspect of scaling-up CCS as they allow for economies of scale through sharing of infrastructure and accelerated learnings. Examples of hubs exist in projects such as the East Coast Cluster in the UK and Northern Lights in Norway (The CCUS Hub 2024).

Figure 1.1. CCS projects across the world at the time of publication. The USA and Canada have 21 facilities in operation, 9 in construction, 80 in advanced development and 92 in early development. Europe has 4 facilities in operation, 6 in construction and 109 in early or advanced development. Asia Pacific has 12 facilities in operation, 8 in construction and 34 in advanced or early development. The Middle East and North Africa have 3 facilities in operation, 3 in construction and 3 in advanced development. South America has 1 facility in operation and 1 in early development.



Box 1.1

Examples of CCS projects from around the world which have been operating for a number of years.



Source: Halliburton

The CCS value chain consists of three key components: capture, transport, and storage (Figure 1.2). The CO_2 capture process is well established and effective. Energy producers and industrial emitters such as cement and chemical manufacturers can leverage CO_2 capture technology to capture CO_2 emissions generated from burning fossil fuels during their operations. Direct air capture involves removing CO_2 directly from the atmosphere. This capture method is not used at the point of CO_2 emissions and at present can only capture small volumes of CO_2 relative to industrial capture methods.

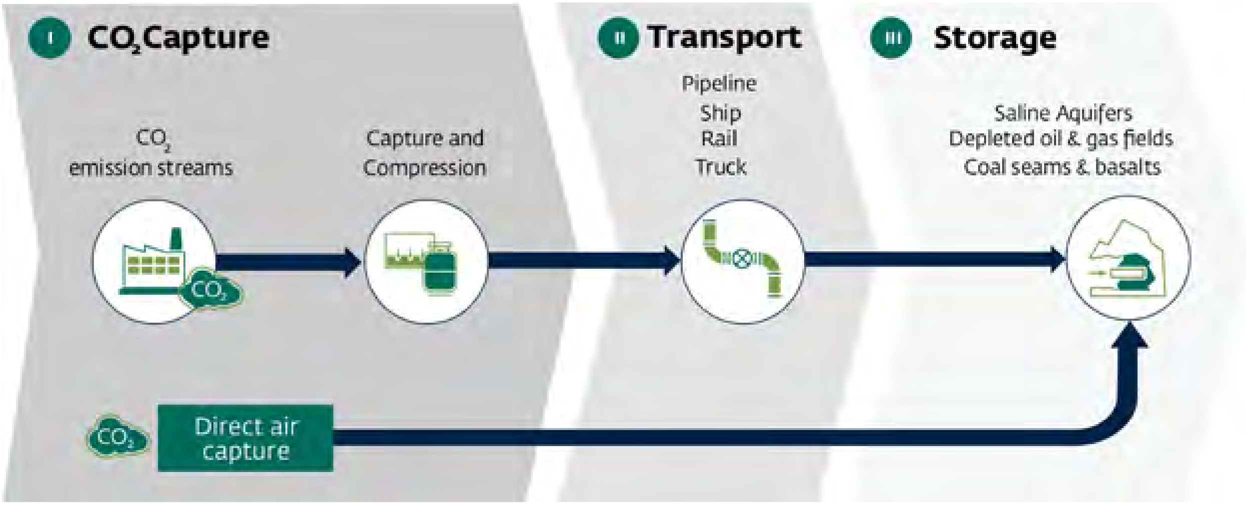
Commercial-scale transport of CO_2 uses pipelines, tanks, and ships to transport CO_2 in gaseous and liquid forms from the capture site to the storage site. Pipelines are the most favorable way for moving large qualities of CO_2. Trucks and rail may also be used to move CO_2, albeit on lesser scale than pipelines.

CO_2 storage is the final stage of the CCS process and involves injecting the captured CO_2 into geological formations for long-term storage, thus permanently removing it from the atmosphere. Saline aquifers and depleted hydrocarbon fields present the most common storage options. Lesser developed alternatives are coal seams and basalt formations. There are extensive storage resources available in the world and they exist in almost every nation.

1.4 Role of this Atlas

The purpose of this Atlas is to provide an overview of Nigeria's potential for CO_2 storage and establish a starting point to support the identification of CCS opportunities. Its primary aim is to highlight locations which have the potential for the long-term geological storage of CO_2. The information on these locations provides a foundational insight into the core aspects needed to make a CCS storage site viable. Subsequent analysis, investigations and extensive data collection would be needed to verify the suitability of any site shown in this Atlas. Whilst CO_2 storage potential is the main focus of the Atlas, it also includes an overview on Nigeria's locations for CO_2 sources and potential transportation networks, which help to complete the picture on the key components necessary for CCS projects. The Atlas also aims to indicate some of the challenges which exist in Nigeria

Figure 1.2. The CCS Value Chain



Source: BCG

today in relation to the regulations and infrastructure surrounding CCS. Collectively, this provides an overview of the status of each component of the CCS value chain which is needed to facilitate full-scale future CCS projects.

Out of scope of the Atlas is the consideration of utilization of CO_2, for example enhanced oil recovery (EOR). Hence, all details of the carbon capture, transport and storage life cycle in this Atlas are with reference to potential CCS projects only and not carbon capture, utilization and storage (CCUS).

1.5 Atlas Structure

This Atlas is divided into six chapters. Each chapter addresses a key subject on carbon capture and sequestration in Nigeria:

- Chapter 1: introduces the importance of CCS in Nigeria today within the context of the challenges Nigeria is facing in terms of climate change. A very brief overview of the global status of CCS is also provided to show the role this solution is playing today to help mitigate against climate change.
- Chapter 2: outlines the evolution of Nigeria's journey towards establishing regulations and policies for climate change and CCS. In addition, the chapter indicates the policies Nigeria has today that could help with progressing towards CCS projects but also indicates where potential policies and regulations could be developed to encourage future deployment of CCS.
- Chapter 3: aims to give a high-level perspective on the emissions sources and locations in Nigeria today. A brief overview is provided on the types of emission sources and the range of carbon dioxide volumes that they emit.
- Chapter 4: provides a concise perspective on the distribution of various forms of transport in Nigeria that may have potential for transportation of CO_2 in future CCS projects.
- Chapter 5: introduces the methodology used to assess the storage resources in Nigeria that are presented in this Atlas. It also indicates several analysis methods that were used to help indicate the potential viability of various CO_2 storage resources that have been studied.

- Chapter 6: presents a compilation of potential CO_2 storage resource is in Nigeria. It indicates the likely distribution of CO_2 storage fairways that could be further investigated for their viability as a future option for CCS projects. Also presented is analysis of the varying geological aspects that contribute to the risk and uncertainty in each storage resource described. This section provides an insight into the distribution of CO_2 storage resource for both saline aquifers and depleted hydrocarbon reservoirs. In addition, unconventional CO_2 resources (namely basalts and coal seams) are also discussed for their inclusion as a CO_2 storage option in Nigeria.

1.6 Atlas Data Sources

The creation of this Atlas was made possible by the support and cooperation of the Nigerian Upstream Petroleum Regulatory Commission (NUPRC), National Oil Spill Detection and Response Agency (NOSDRA), Nigeria Geological Survey Agency (NGSA) and Nigerian Midstream and Downstream Petroleum Regulatory Authority (NMDPRA). The Atlas has benefited from maps, reports and data provided by these organizations and the use of this material is kindly acknowledged.

The CO_2 storage component of the Atlas (Chapters 5 and 6) has been compiled using a proprietary dataset (Appendix 2) which itself has been built from sources in the public domain. There are limitations in both volume and resolution of the data available with which to define the geological risks and potential fairway of the storage sites. The Atlas therefore, provides a high-level perspective on where potential locations for CO_2 storage may exist. Indication is also given, where possible, of known geological properties and features which could present a challenge to CO_2 storage.

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2 The Context of CCS in Nigeria

The Federal Government of Nigeria (FGN) has identified that carbon capture and storage (CCS) can play a major role to support Nigeria's energy transition and climate targets. The importance of CCS as a key solution to help Nigeria's decarbonization was explored in 2021 through a collaboration between the Nigerian Government and International Energy Agency (IEA, 2021). Since then, activities relating to the realization of a CCS work program have been conducted between the Office of the Vice President, Federal Ministry of Industry, Trade and Investment and the International Finance Corporation (IFC, part of the World Bank Group) (IEA, 2021, IFC 2022). At the time of writing, the Nigerian Geological Survey Agency (NGSA), with federal backing, is preparing to launch a Center of Excellence for Carbon Management. This Center will be responsible for research and development for unconventional geological storage of CO_2 (including basalts, coal seams) (NGSA 2024).

2.1 The Current Status of Nigerian Regulations for Promoting Climate Change Mitigation

Nigeria's journey towards establishing a robust regulatory framework for climate change mitigation has been characterized by strategic planning and steady progress. In addition to the steps taken to commit to cutting greenhouse gases (GHG), over the past 15 years Nigeria has made several key advances in policies and regulations for climate change mitigation, as shown in Figure 2.1.

a) Foundational Policies and Initiatives (pre-2010)

A foundational phase began with the establishment of the National Environmental Standards and Regulations Enforcement Agency (NESREA) in 2007, which set the stage for environmental protection and sustainable development efforts in Nigeria.

b) Strategic Development and Planning (2010 - 2015)

Further reinforcing the country's commitment to climate change mitigation, Nigeria developed the National Policy on Climate Change in 2012, a critical document that set the groundwork for addressing greenhouse gas emissions and integrating climate change action into national planning. This was followed by the formation of the National Adaptation Strategy and Plan of Action on Climate Change in 2012, aimed at creating resilient systems and processes to adapt to climate-related challenges.

c) Accelerating Climate Finance and Legislation (2015 - 2020)

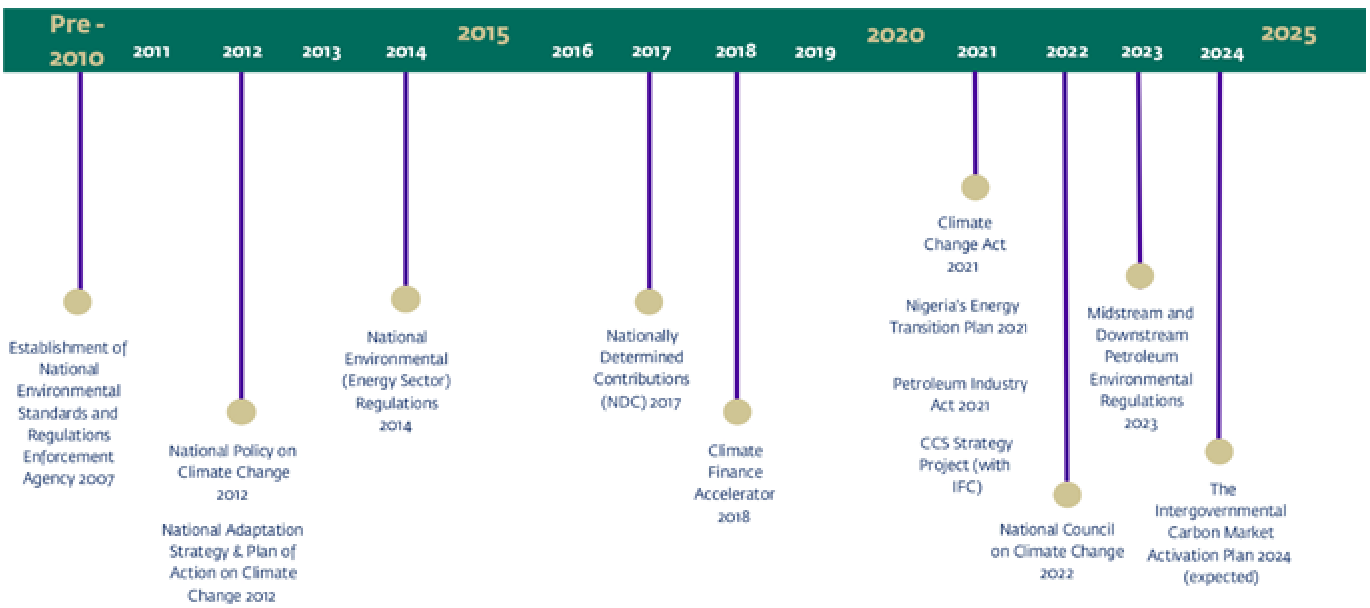
By 2017, Nigeria had formulated a Sectoral Action Plan for its Nationally Determined Contributions (NDC) to the United Nations Framework Convention on Climate Change (UNFCCC), intending to boost emissions reduction across key economic sectors. The establishment of the Climate Finance Accelerator in 2018 marked a significant move towards providing the necessary technical and financial expertise to support Nigerian climate projects in securing investments.

d) Recent Actions and Future Outlook (post 2020)

The passing of the Climate Change Act in 2021, which provided a robust legal framework for achieving national climate change goals, laid the foundation for an efficient sustainable carbon market ecosystem and helped consolidate Nigeria's strategy.

Nigeria's Energy Transition Plan, announced in 2021, signals the country's ambitious commitment to achieving net-zero emissions and ensuring full energy access by 2060. This plan emphasizes the role of CCS in Bioenergy with Carbon Capture and Storage (BECCS) to help both energy and non-energy industries to achieve net zero. Furthermore, the creation of the National Council on Climate Change (established in 2022 by Section 3 of the Climate Change Act) intends to focus on comprehensive climate change mitigation and adaptation measures. Amongst many functions, the Council is charged with developing and implementing a mechanism for Carbon Emissions Trading and also implementation of a carbon tax. In 2022, the International Finance Corporation began working with the Federal Government of Nigeria to develop a domestic market for carbon capture and storage for industrial emissions, in part through the creation of this Atlas. The most recent activity is the Intergovernmental Carbon Market Activation Plan (planned 2024), which indicates the nation's intent to establish a blueprint for driving an efficient sustainable carbon market ecosystem.

Figure 2.1. Nigeria's progress on initiation and development of policies and regulations which help facilitate climate change mitigation and future CCS development.



Source: BNRCC 2011, NESREA 2014, Federal Ministry of the Environment 2021(a, b), FGN, 2021(a, b), NUPRC 2021, NMDPRA 2023, National Energy Transition Plan 2024

2.2 Nigeria's Current Policies and Regulations which Support CCS

At the time of writing, Nigeria has several regulations which could help support the future development of CCS in the country:

- The Nigerian Upstream Petroleum Regulatory Commission (NUPRC) (NUPRC, 2021) has incorporated CCS into one of the draft regulations released on acreage management and stated that, "with the consent of the Commission, the lessee may provide carbon capture and storage services with respect to reservoirs contained in the lease area". In addition, the Petroleum Industry Act, 2021 (FGN, 2021) recognizes the need for decarbonization and requires each concessionaire of a petroleum license to incorporate an environment plan in its field development plans to mitigate against adverse environmental impacts. CCS arguably has the potential to be included in future plans as part of the decarbonization effort.
- The National Midstream and Downstream Petroleum Regulatory Authority (NMDPRA) Midstream and Downstream Petroleum Environmental Regulations 2023, has a dedicated section relating to climate change which outlines GHG

management. Specifically, these require a licensee to monitor GHG from its activities and operations, estimate GHG volumes and report the information in accordance with Authority guidelines. In addition, the licensee shall develop and submit a strategy for carbon capture, decarbonization and achievement of net zero targets in its operations to the Authority for approval (NMDPRA, 2023). These are supportive for a future CCS industry in Nigeria.

- The National Environmental Standards and Regulations Enforcement Agency (NESREA), whilst not specifically having laws pertaining to CCS operations, does outline best practices for controlling emissions from the energy sector and the application of methods to reduce emissions. This also lists GHGs as a component of those emissions (NGSA, 2014).
- The Nigerian National Petroleum Corporation (NNPC) is the regulator of all hydrocarbon licenses; they also operate joint ventures or production sharing contracts with international oil companies and other independent operators. The NNPC is actively supporting the energy transition momentum by investing in new energy and has a long term decarbonization programme.

2.3 Current Status to Support CCS Storage Projects

In terms of the current regulatory landscape, there are policies and regulations which could facilitate development of a CO_2 storage pilot project.

A CO_2 storage pilot project is small scale, typically injecting less than 100,000 tonnes of CO_2. The projects are often initiated by research bodies and/or developers and operators from the CCS value chain. The aim is to provide evidence, data, and testing opportunities for all or specific stages of a CCS project at a modest cost of investment. Some pilot projects may precede larger scale projects. Costs can vary from $2 million to $8 million. CO_2 may come from a variety of sources (natural, emissions based, food grade (Cook et al. 2014)) depending on the scale, and financial constraints of the project, and may be transported by road, rail, or ship (e.g. Project Greensands, Denmark (Szabados and Poulsen, 2023)) as opposed to dedicated pipelines due to the small quantities of CO_2 involved (Veloso et al. 2022). The injection phase is designed to answer many questions relating to injection, behavior of the storage site and CO_2 plume migration and safety issues. Due to data availability and familiarity with site characteristics, many pilot sites are either in, or close to, producing or depleted hydrocarbon fields. Monitoring is an integral part of a storage pilot which starts early in the project and continues beyond final injection.

For CO_2 storage pilot projects, the areas in the existing regulatory framework which may be sufficient to support them include:

- Permits: adjustments to existing laws are necessary to designate a regulator with the authority to oversee all regulatory and permitting decisions for CCS. The NUPRC has existing legislation that can be expanded to included CCS activities (Petroleum Industry Act, 2021) and the NMDPRA's Midstream and Downstream Petroleum Environmental Regulations 2023, includes a section on strategy submissions for carbon capture and decarbonization.
- Resource uses: the NUPRC regulates subsurface pore space ownership and hence current regulations may support the pilot phase. However, a clear and streamlined legal framework, especially for subsurface permitting, is necessary for full-scale deployment.

Many storage pilots have proceeded as research projects outside of a standard CO_2 storage permitting regime. Examples of this are the Illinois Basin – Decatur Project. This is a one million tonne saline CO_2 storage project and was initiated before the United States carbon storage regulatory framework was fully developed. The project progressed within existing regulations whilst waiting on new regulation development but did take many years. To help with progress and uncertainty, the project also built a risk-based monitoring strategy that aimed to go over and above the expected future regulations requirements (Locke et al. 2017).

2.4 Current Regulation Gaps in Nigeria for CCS

The regulation of CCS is critical to its success in Nigeria. CCS projects are complex, and each part of the value chain will need its own regulations and standards which must be overseen and approved by regulatory organizations (see Box 2.1 for the three key dimensions for a successful CCS project).

2.4.1 Future Regulation Opportunities

The regulatory landscape in Nigeria involves multiple authorities, each with jurisdiction over distinct segments of environmental and energy regulation. By expanding existing regulatory frameworks, there is potential to create a cohesive and comprehensive policy environment which supports the advancement of CCS technologies, aligns with international best practices, and contributes to sustainable energy development.

- Capture
  - Regulating capture standards from server industries falls under the purview of NMDPRA.
- Transport
  - The NMDPRA currently oversees the transportation of oil and gas products and could expand its purview to include the transport of CO_2 (see Box 2.1 for an indication of regulation scope).
  - Other ministries and departments which have a vested interest in ensuring CO_2 is transported safely and effectively are those involved with forms of transport where CO_2 carriage could affect existing infrastructure/ operations. The Ministry of Transport, for example, could provide regulations on CO_2 transport by rail. If CO_2 was moved by ship, then the Nigerian Maritime Administration and Safety Agency (NIMASA) has authority over regulations to ensure safe transport of CO_2 from an environmental and logistics aspect.
- Storage
  - The NUPRC regulates subsurface pore space ownership, which is a core aspect of CO_2 storage in depleted hydrocarbon fields. In addition to storage site regulations during injection, there would be a need to develop regulations on monitoring, measuring and verification (MMV). This is a critical aspect of the storage component for a CCS project and needs to ensure that all necessary and proportionate measures are taken to monitor the safe containment of CO_2 post -injection (see Box 2.1 for an indication of regulation scope).
  - The environmental studies and assessment regulations of the NMDPRA's Midstream and Downstream Petroleum Environmental Regulations 2023, include Project Concept Screening (PCS), Preliminary Environmental Risk Assessment (PERA), Environmental Evaluation Study (EES) and Post Impact Assessment Study (PIA). These could be adapted for future CCS storage project needs and permit development (see Box 2.1 for an indication of permits).
  - In relation to regulations for storage in saline aquifers and unconventional CO_2 storage (basalts and un-mineable coal seams) the NGSA would be able to provide geological specifics. However, the type of resource will determine differing stakeholder inputs, for example, when injecting in saline aquifers CO_2 is most often in a supercritical state, but when injecting in basalt formations the CO_2 is dissolved in water and injected in an aqueous state (IEAGHG, 2017). This requires large amounts of water and may well need the intervention of NESREA for water resource regulations and management.

Finaly, Nigeria does not yet have specific CO_2 storage standards. This would need to be in place for CO_2 projects to be enabled. The International Standard Organization (ISO 2011) has developed CCS standards (under ISO Technical Committee 265 (ISO/TC265)) which aims to ensure that CCS is globally practiced in a safe and correct manner. These have been developed since 2012

Box 2.1

Key Regulation Dimensions for CCS Deployment

The deployment of CCS projects on a global scale hinges on three core dimensions: environmental and regulatory requirements, commitments and standards, and economic mechanisms. Understanding these dimensions is crucial for effective policy and project implementation (IEA, 2022).

A. Environmental and Regulatory Requirements

- Permits: CCS projects require comprehensive permitting frameworks that govern the capture, transport and storage of CO_2. This regulatory clarity is paramount, particularly in protecting against CO_2 leakage. In addition, drilling and operational permits are necessary to ensure that the entities involved in CCS projects can legally and safely manage subsurface activities.
- Resource uses: effective utilization of resources such as land and pipeline infrastructure are essential. Access to land is critical for pipeline and storage infrastructure and may involve balancing the rights of landowners with the public interest in reducing carbon emissions.
- Liabilities: addressing long-term liabilities, such as site closure.
- Cross-border issues: international CCS projects will need to accommodate transboundary legal considerations.

B Standards, Strategies & Targets:

- Standards: establishing transparent standards for CO_2 capture, transport, and storage will help facilitate classification, ownership, and life cycle management.
- Strategies and targets: clarity in the strategic role of CCS within a decarbonization pathway is necessary for aligning national goals with the practical deployment of these technologies.

C. Economic Mechanisms

- Financial incentives: economic incentives are a driving force for the advancement of CCS.
- Support for infrastructure and technology; major types of financial support include:
  * Carbon cost: carbon pricing mechanisms provide economic incentives for reducing greenhouse gas emissions. This includes tools such as carbon taxes, Emissions Trading Systems (ETS), and Low Carbon Fuel Standards (LCFS).
  * CCS development & scaling: incentives to bolster the economic aspects of CCS, such as grants or subsidies, can promote the scaling of the technology.
  * Infrastructure development: financial support is crucial for the development of shared infrastructure which connects supply and demand nodes within the CCS network.
  * CCS technology & demonstration: advancing multiple technologies in the CCS value chain is necessary to achieve commercialization; grants and tax credits can support this advancement.

The IEA's Policies and Measures Database provides access to government policies (past, present and planned) which cover greenhouse gas reduction, energy efficiency, renewables and other clean technologies (IEA).

and are widely accepted around the world. Most countries develop their own standards specific to the conditions and needs of the country. However, the ISO standards provide global applicability to CCS and hence a foundation for countries to follow when developing their own standards. There are currently 13 published standards by ISO/TC 265 which cover the activities of capture, transportation, utilization and storage. The standards encompass the design and construction of facilities, operations, environmental planning and risk management, safety management, quantification, and monitoring across the CCS value chain.

2.4.2 Scope of Regulations Needed for the CO_2 Storage Phase of a CCS Project

To implement full-scale CCS projects, Nigeria will need to introduce several CCS-specific regulations. Whilst Box 2.1 indicates the core regulatory dimensions necessary across the full value chain, Figure 2.2 shows where legal and regulatory issues need to be addressed at each stage of the storage phase of a CCS project (IEA 2022). The overarching focus of any storage project is the safe and secure geological containment of CO_2 and hence focus is placed on outlining the legal and regulatory issues that are needed to ensure this.

The resource and site selection phases are defined by finding a suitable geological site for CO_2 storage and understanding how effective it is at trapping and containing CO_2 for the long-term A strong focus here is placed on environmental considerations. Legal and regulatory frameworks need to ensure that only suitable storage sites are developed. Norway, the European Union (EU), Australia, and the USA have all defined and employed specific approaches to this task. Pore space ownership is clearly defined in Nigeria so legal issues here are of less concern. Issues relating to contamination of adjacent resources (e.g. aquifers for potable water resources) need to be defined and legislated.

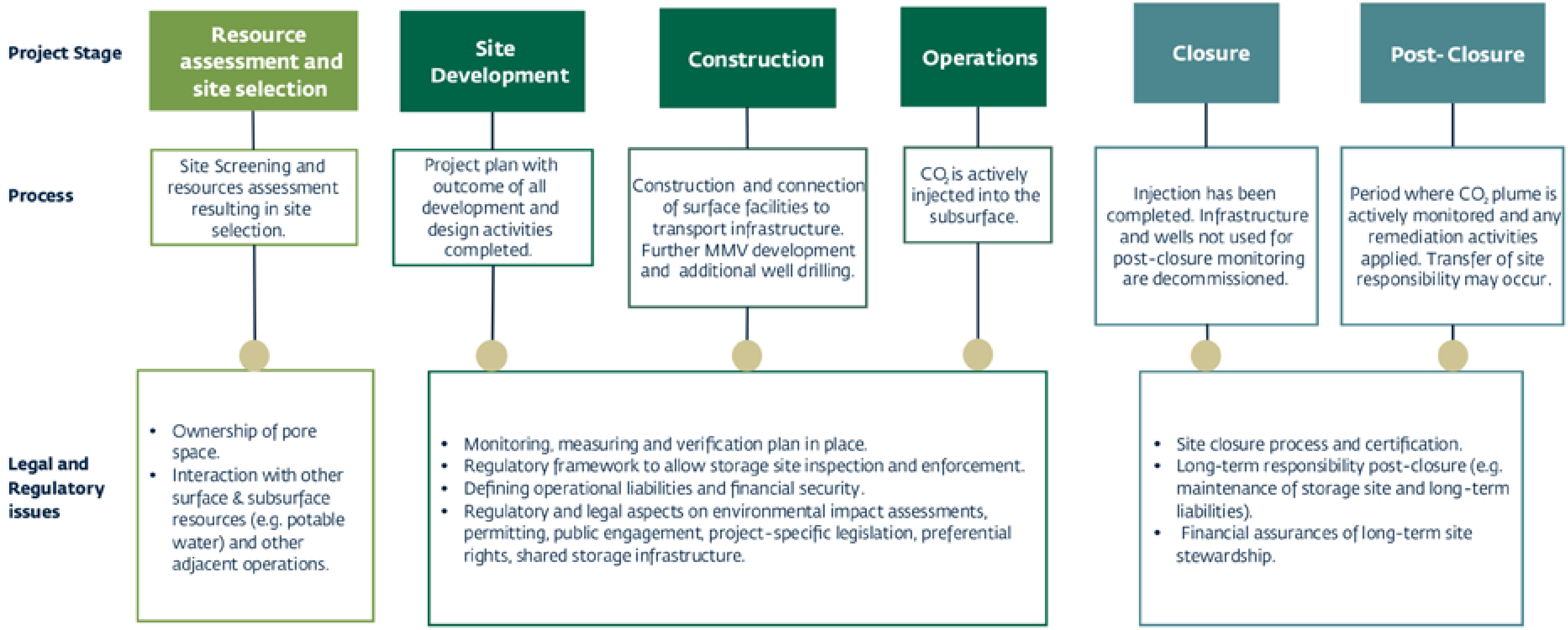
During the site development to site operation phase, regulations and legal aspects become more complex. A fundamental aspect of this stage is the monitoring, measurement, and verification (MMV) plan (See box 5.2). MMV plans are to ensure safe and secure operations and minimize CO_2 migration or leakage. Following ISO 27914 (ISO 2017), leakage is defined as unintended release of fluid out of a pre-defined containment or storage complex. This means that migration is acceptable as long as it is within the storage complex.

Countries actively engaged in CO_2 storage such as Australia, Canada, the USA and those in the EU, have specific requirements for MMV plans but also the cadence at which monitoring is carried out, reported and updated. In a similar vein, site inspection regulations vary amongst countries but allow regulatory authorities to take enforcement measures if necessary.

In terms of operational liabilities and financial security, it is widely accepted that the storage site operator should bear the liability for damage during any storage site operations and beyond. This liability may well extend to the long-term stewardship of the site. Here, existing hydrocarbon, mining and waste disposal regulations could provide relevant models for regulation frameworks. During the post-closure phase, regulations would need to be established in Nigeria on who the responsibility of the site would be transferred to.

One project that can offer a case study on the implementation of CCS projects under either no legislation or emerging legislation is the Otway Basin project in Australia. Although the project was only designed for injecting quantities that were nowhere close to commercial scale operations, it does provide a perspective on how legislation was developed. The Otway Basin project, which was Australia's first carbon storage project, was initiated in 2004 with work starting at the site in mid-2006. Several regulatory bodies were involved as the project progressed. At the initial stage the petroleum industry regulator (Department of Primary Industries – DPI) approved flow testing of the site well. After this, three key authorities (the DPI, Environmental Protection Agency (EPA) and Southern Rural Water (SRW)) liaised to define how to regulate this kind of project. The progress of the project was pushed forward with significant financial input from the Australian government to drill the first storage well in February

Figure 2.2. Stages and processes of the CO_2 storage phase of a CCS project and the relevant legal and regulatory issues which need to be addressed.



Source: Modified from IEA 2022

2007. Once approvals were granted from the EPA and SRW for Stage 1 of the project, injection commenced in April 2008. Stage 2 of the project was approved in January 2010, but regulations were not yet advanced enough to cover its continuation, so specific regulations were enabled to allow Stage 2 to progress. One challenge this project faced was how it should be regulated. It was decided that the most appropriate overarching legislation would be to regulate the project under research, development and demonstration provisions of the Environmental Protections Act 1970. The EPA then sought advice and approvals from other regulatory bodies for specific activities in the project (e.g. drilling activities from the DPI). The success of the project was facilitated by a thorough assessment and identification on every aspect of the operations that need regulatory approval (Ranasinghe 2013). See Box 2.2 for an outline of core lessons learnt for establishing a regulatory framework from this project.

Brazil also offers a case study in the implementation of CCS projects under emerging regulatory frameworks. Box 2.2 shows the evolution of the regulatory framework before and after the development of a CCUS project in this country. Brazil has made significant advancements in CCS despite a nascent regulatory framework at the outset. These developments imply that governmental initiative and backing, especially in state-owned sectors, can propel CCS projects even in the absence of mature regulatory systems. Both Australia and Brazil show that the establishment of regulatory frameworks can be a responsive rather than a proactive process, evolving to meet the needs and complexities of ongoing CCS projects.

South Africa, which has been taking steps towards establishing a CCS industry over the past 20 years, provides a third example for initiation of CCS projects. The country's CCS roadmap began in 2004 when the government started investigating CCS as a method to reduce CO_2 emissions from coal-fired power stations. In 2009, the South African Center for Carbon Capture and Storage was established which resulted in the development of the South African CO_2 Geological Storage Atlas the following year. It then began establishing a pilot CO_2 storage project in 2017, aiming for a commercial project by 2025 (Beck, 2013). There have since been some delays to this progress. South Africa is in the early stages of developing its policy framework for CCS and it is yet to be established sufficiently to encourage wider CCS momentum in the country (Ko et al. 2011, International PtX Hub 2023). CO_2 is classified as a pollutant in South Africa (Department of Environmental Affairs, 2017). South Africa provides an example from the African continent that demonstrates, in the absence of a robust CCS policy framework, how CCS projects can begin and especially how pilot projects can be planned with a vision to segue into a commercial project.

CCS presents an opportunity for Nigeria to achieve its climate commitments (such as those described in its Nationally Determined Contributions and Climate Change Act), whilst maintaining the necessary industrial development pace. It also offers the opportunity to develop a highly-skilled industry that can create value for the country by leveraging Nigeria's gas industry. Although the number of CCS projects are growing globally, there are few on the African continent.

Nigeria already has several policies and regulations which can be built upon to develop a CCS policy and regulations framework. As has been demonstrated in other countries, this framework can be developed in tandem with, or using lessons learned from early mover projects and pilots.

Box 2.2

Development of Regulatory Frameworks in Brazil and Australia

Brazil

The Petrobras Santos Basin pre-salt oilfield CCUS pilot project, initiated in 2011. Capacity 3-10.5 Mt CO_2 /year

Regulations Before Project Launch

- Regulatory support was not established, reflecting the nascent stage of Brazil's legal framework for CCUS.
- Emissions targets and commitments were present but without a structured approach.
- Economic mechanisms were limited due to the absence of a regulated carbon market.

Regulations After Project Launch

- Establishment of a dedicated committee to develop legal frameworks for CCUS.
- Draft of the Fuel of the Future bill to provide a legal foundation for CCUS framework.
- Plans for appointing the National Petroleum Agency as the CCUS regulator.
- Publication of a decree to create a regulated market for carbon credits.

Brazil's case study reveals the importance of progressive policy development in advancing CCS technologies. By leveraging research and development, integrating policies across government agencies, and establishing market mechanisms for carbon credits, Brazil has successfully transitioned from limited initial regulatory support to a more structured legal and regulatory framework for CCS.

Australia

Otway Basin pilot project (Victoria, Australia). Site work commenced in 2006 The site continues to operate today as a test site for CCS research.

Regulatory Timeline

- An absence of domestic CCS-specific regulation existed in Australia at the start of project initiation in 2004.
- It took 4 years of approvals and discussions to reach start of injection into Australia's first CO_2 storage well.

Lessons Learnt

- Adequate time and resources need to be allocated for project approvals.
- Project operators and regulators should collaborate at the concept phase.
- Project approvals should be appropriate depending on the scale and the impacts.
- All relevant authorities need to be consulted depending on their expertise.
- Petroleum industry regulations provide a basis for carbon storage regulation.
- Water authority approvals are important for regulating carbon storage projects.
- Adequate time and resources need to be allocated for any land access issues.
- Transitional regulations need to provide for projects in existence whilst new legislation is developed.
- Discussions should commence early in the project planning phase to clarify distribution of liability over time.
- Stakeholder engagement is a critical part of any project and needs to be managed carefully.

The success of this project was achieved by continued work between the operator of the project and the Victorian Government. The regulators addressed the challenges in a creative way and developed a regulatory framework in tangent with the project. A clear matrix of regulatory responsibility for each activity in the construction, operation and closure stages were also established at Phase 1 of the project.

Source: IEA 2022, GCCSI 2015, OGCI, 2021, Rocha et al. 2021, Ranasinghe 2013

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3 Overview of CO_2 Sources

In Nigeria, CO_2 emissions are relatively low compared to global levels. They are, however, the second largest in Sub-Saharan Africa and expected to grow significantly in the coming years. Therefore, the country has an important role to play in addressing climate change. Today, operational industrial emissions are at 28 Mtpa but this is projected to grow by 3-5% annually, indicating a potentially significant increase over the next 40 years if no abatement measures are taken.

Carbon capture and storage (CCS) is best suited to large stationary emitters and has mostly been applied to fuel transformation (natural gas processing) with small amounts of power generation (coal) and industrial producers (e.g. steel, chemicals, cement). These are hard-to-abate industries and require CCS as the core component of their emissions reduction portfolios (IEA 2023). In the 2023 IEA Net Zero Emission (NZE) scenario, CCUS* along with hydrogen and hydrogen-based fuels provides one-fifth of all emissions reductions between 2030 and 2050. To reach NZE scenario, at least 1 Gt of CO_2 must be captured per annum by 2050.

Nigerian CO_2 sources presented in the following section are those which are from stationary, hard-to-abate CO_2 emissions sources, namely heavy manufacturing industries and the energy industry. The energy sector is a significant element in Nigeria's economy, thus there is a prevalence of energy sector facilities that are relevant to CCS. Heavy industry is hereby defined as facilities that have Industrial Processes and Product Use (IPPU)** as their primary activity.

Nigeria's main non-industrial emissions include transport, agriculture, and residential/commercial consumption. These industries are not as well aligned to be part of a CCS value chain as industry and energy, but may become more so in the future. The contribution to the country's CO_2 emissions from these non-industrial sources is significant. In line with population growth, emissions from the buildings, agriculture and transport sectors have seen a steady increase since 1990 (Crippa et al. 2023). Transport contributed up to 56% of Nigeria's total energy-related CO_2 emissions in 2021 (the analysis did not include direct CO_2 generation, e.g. from cement) (IEA 2021a). In addition, agriculture, forestry, and other land use (which includes activities such as livestock farming, harvesting of wood products, crop production and biomass combustion) is another major emissions group and Nigeria's second largest contributor to greenhouse gases after energy (Federal Ministry of Environment 2021).

* The source reference states capture volumes relating to CCUS. Hence, CCUS is the term used here since differentiation of capture volumes relating to CCS and CCUS are not reported.

** As defined by the IPCC common reporting framework to include mineral industry (e.g. cement), chemical industry (e.g. petrochemicals), metal industry (e.g. steel) and others.

3.1 Stationary Sources in Nigeria

The methodology used to compile a review of Nigeria's CO_2 sources involved extensive research, the details of which are described in Appendix 1.

Based on operating capacity it is estimated that Nigeria's industrial CO_2 emissions are 28 Mtpa. The CO_2 emissions (Table 3.1) are produced from three sector categories: cement manufacturing which accounts for 77%, ammonia/fertilizer manufacturing which accounts for 21%, while other chemical synthesis (e.g., petrochemical) account for <2%. Steel production and paper manufacturing could potentially add just over 1 Mtpa to Nigeria's industrial CO_2 emissions, but the related facilities are currently operating at very low levels. It is expected that further CO_2 emissions (Table 3.1) could be added by upcoming facilities which have expectations for being online by 2025. Nigeria's energy industry is by far the greater source of CO_2 emissions compared to industrial sources at 38 Mtpa.

In terms of number of emitters (Figure 3.1), there are 100 existing and upcoming emitting facilities with CO_2 output exceeding 100 kilotonnes per annum (Ktpa) within Nigeria and its offshore territories:

- Total emitters: there are 84 existing CO_2 emitters and 16 upcoming CO_2 emitters with reasonable expectations of coming online by 2025. Of those currently in existence, 77 are operational.
- Industrial emitters: there are 18 existing industrial CO_2 emitters and 15 of these are operational. There are 7 upcoming industrial CO_2 emitters that have reasonable expectations of being commissioned and operational by 2025.
- Energy emitters: for the energy sector, there are 66 CO_2 emitters of which 62 are operational. There are a further 9 upcoming energy CO_2 emitters.

The proximity and concentration of CO_2 emissions sources to Nigeria's potential CO_2 storage resources are important considerations, to ensure that transport costs do not negatively impact a CCS project's success or compromise the net capture of CO_2. Chapters 4 and 6 of this Atlas will present the location of current transport networks and proximity of CO_2 storage opportunities to Nigeria's emissions sources, thereby providing a starting point for future strategies to identify potential CCS projects.

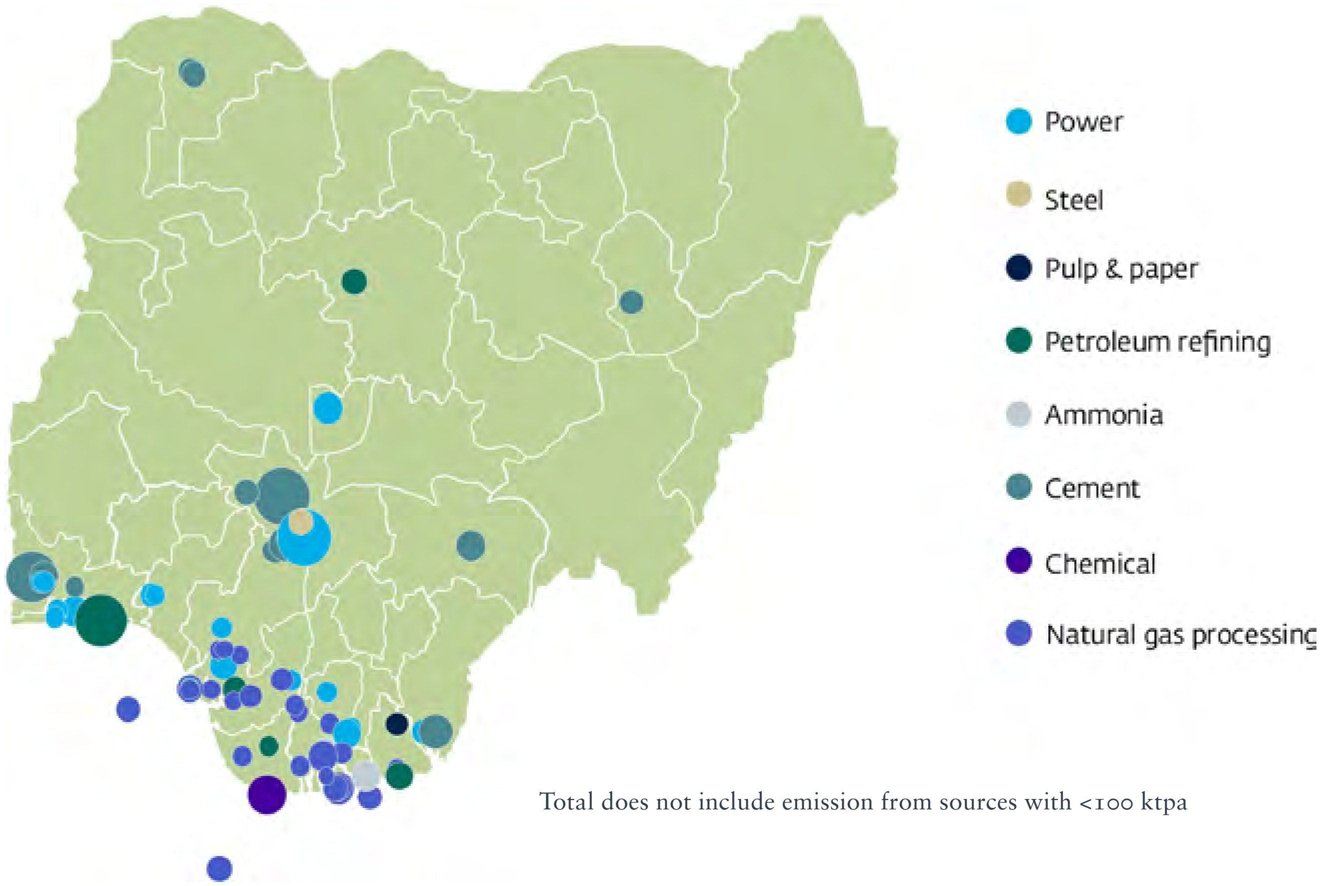
In addition, like all components of the CCS value chain, there will need to be policy and regulations relating to the capture of CO_2 emissions. Chapter 2, section 2.2 of this Atlas indicates which regulations will need to be developed to facilitate future CCS projects from the capture perspective.

Table 3.1. Estimated CO_2 emissions from sources in Nigeria (based on analysis performed in 2023. See Appendix 1 for details).

Sector Category	Existing (Mtpa)		Upcoming (Mtpa)	Total Identified (Mtpa)
	Operational	Non-Operational		
Cement	21.67	0.00	1.27	22.94
Ammonia/ Fertilizer	6.00	0.00	3.32	9.32
Chemical Synthesis	0.46	0.00	3.27	3.73
Steel/Iron	0.00	1.37	1.30	2.67
Pulp, Paper & Packaging	0.00	0.12	0.00	0.22
Total Industrial	28.13	1.49	9.16	38.78
Gas Power Generation	16.16	0.00	2.96	19.12
Natural Gas Processing	19.06	0.00	0.58	19.63
Petroleum Refining	0.00	5.69	6.95	12.64
Coal Power Generation	0.00	0.00	5.81	5.81
Oil Power Generation	1.13	0.56	0.00	1.69
LNG	1.56	0.00	0.00	1.56
Others	0.12	0.00	0.00	0.12
Total Energy	38.03	6.25	16.30	60.57

Source: BCG

Figure 3.1. Locations and types of CO_2 sources in Nigeria. The smallest baseline circle represents emissions of 100 Ktpa CO_2, with progressively larger circles indicating higher emissions.



Source: BCG

3.2 Key Sectors Driving CO_2 Emissions in Nigeria

The key sectors driving CO_2 emissions in Nigeria which can be potentially mitigated with CCS are the energy and industry sectors. The following summary of emissions figures for each sector relates to those facilities that are operational, unless stated otherwise.

3.2.1 Energy Sector

Activities in the energy sector which are relevant to CCS are thermal power generation (gas, oil, and coal), natural gas processing, liquified natural gas (LNG) and petroleum refining. Facilities operating in these sectors outnumber those in the industrial sector by 4:1 and emit almost 1.5 times the volume of CO_2. The prevalence of energy sector facilities in comparison with industrial sites can be explained by Nigeria's prominence as an oil and gas producer (OPEC 2022). The energy sector's CO_2 emissions may jump by 40% in the next 3 years if all upcoming facilities are commissioned as currently planned. CO_2 emissions from existing energy sector facilities primarily come from natural gas processing (50%) and gas power generation (43%).

In the energy sector, emitters produce 38 Mtpa of CO_2 emissions, and this could rise by 17 Mtpa within 3 years if upcoming facilities materialize as planned/committed. This addition would come from petroleum refining (7 Mtpa), coal power generation (6 Mtpa), gas power generation (3 Mtpa), with the balance split between LNG and natural gas processing.

Power Generation

CO_2 emissions for energy sector facilities vary by sector category. For thermal power generators CO_2 emissions are primarily a result of combustion, which is burning fossil fuels to generate heat energy for conversion to electrical energy. The majority of Nigeria's power generation is from gas power plants. These are located in the South-South region (55%) (Figure 3.1), close to gas - their fuel source. A significant proportion are in the South-West (26%), close to economic activities. CO_2 emissions from gas power generation contribute 43% to the overall figure. Coal is primarily used by industry in Nigeria. At present there are no operating coal power plants in the country (IEA 2021a). However, the Nigerian government continues to explore the use of coal for electrical power generation and several plants are expected to come online in the next decade (ITA 2023). To meet new Net Zero Emissions (NZE), CCS may well be an essential part of enabling sustainable coal power generation. At present there are no operating oil-fired power plants in Nigeria. Oil is mainly used in the transport sector with a smaller proportion used by industry (IEA 2024).

Gas Processing

Emissions from natural gas processing systems (and LNG plants) arise from power generation to drive heavy equipment, e.g. compressors and liquefaction units, from fugitive emissions at plants and along transportation networks. All natural gas processing plants are located offshore or in the South-South region (Figure 3.1) as this is where gas production is taking place. Gas processing is a major contributor to Nigeria's energy sector emissions at 50% of the overall figure.

LNG

LNG is the third highest CO_2 contributor at 4%. There is a single LNG facility in Nigeria, and this is located in the South-South (Figure 3.1).

Refineries

Nigeria's refineries are located in the South-South and South-East regions (Figure 3.1), with the largest being located the South-South. Today their production level is substantially below capacity, rendering them effectively non-operational.

3.2.2 Industrial Sector

Cement

Nigeria's cement manufacturing sector (Box 3.1) is highly geographically concentrated, with only three enterprises controlling the majority of market share. Cement plants are mostly located close to the sites of limestone reserves in the country. Due to proximity of key markets and ports, 60% of CO_2 emitted from cement manufacturing occurs in the south of the country. The remaining 40% is emitted in the North-Central zone, specifically in Kogi state.

Ammonia Manufacturing

Ammonia production is the second highest contributor to industrial CO_2 emissions in Nigeria (Box 3.1) and a marked increase is expected over the next three years from planned/committed facilities. About 70% of ammonia (IEA 2021a) is used for production of nitrogen fertilizer. Growth of this sector is driven by population expansion, which is pushing increasing demand for agricultural production and yield. Proximity to natural gas resources in the South-South region (Figure 3.1) influences the location of ammonia plants, hence almost 40% of current CO_2 emissions are from this region. The single emitter accounting for the other 60% is in the South-West and co-located with an upcoming refinery with access to piped natural gas.

Other Chemical Synthesis

Other chemical synthesis (Box 3.1) refers to manufacture of all other chemical products apart from ammonia. Petrochemicals are often co-produced with ammonia, therefore, the expected boom in ammonia production is pushing growth of petrochemicals and there is a strong export market for these products. CO_2 emissions from existing facilities are generated from a single source in Rivers State, close to feedstock (natural gas liquids).

Box 3.1

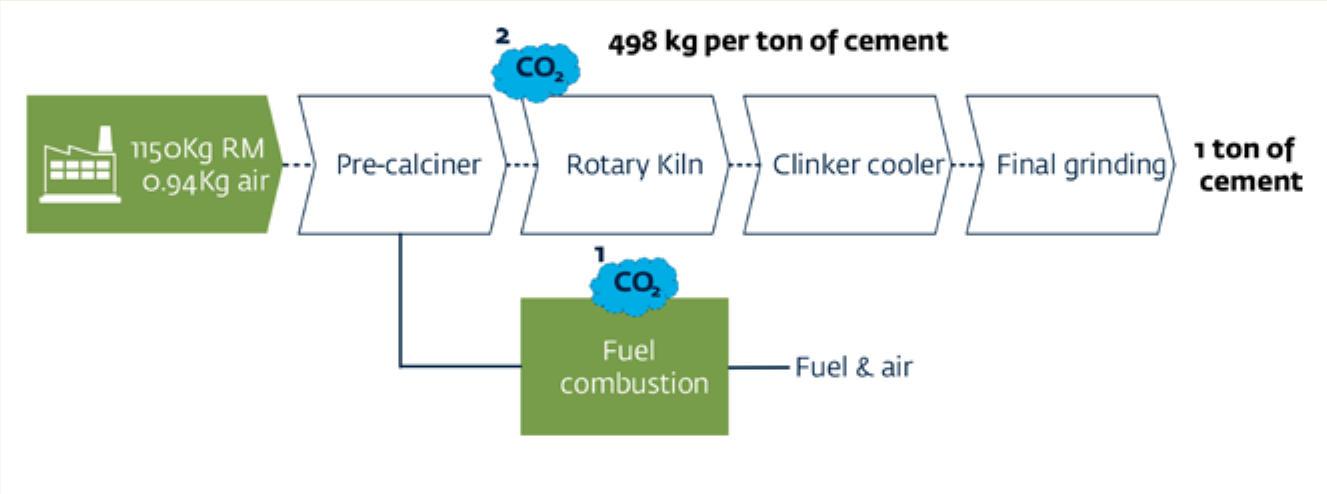
CO_2 Emissions from Industrial Processes

Cement

Process flow of cement manufacture with CO_2 emission streams.

1.CO_2 generated from burning of fuel to generate power for heating

2.CO_2 formed when limestone and clay is heated to form clinker



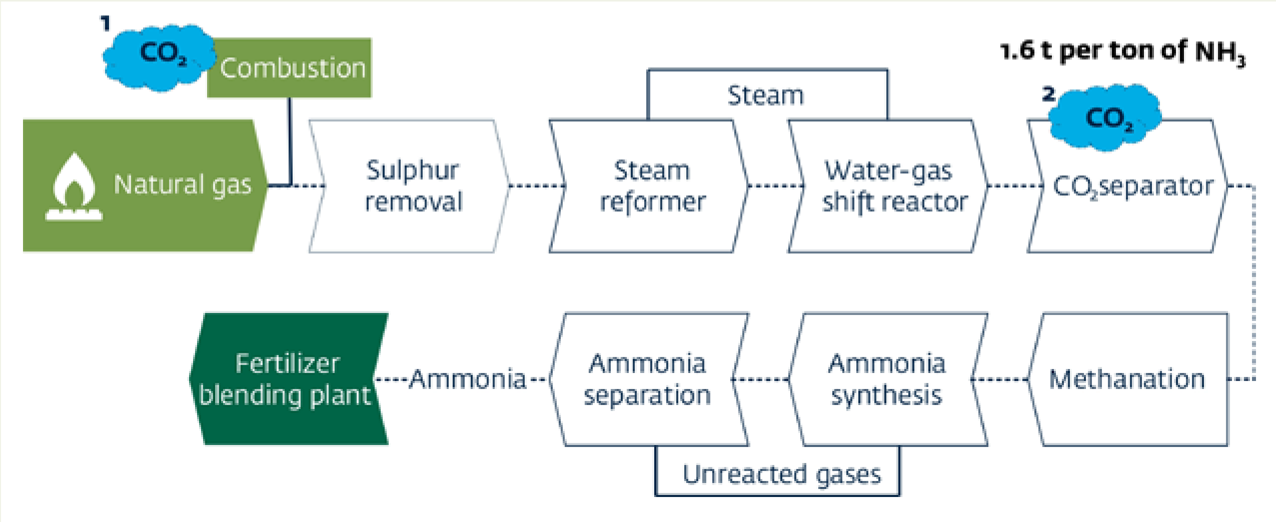
Source: Adapted from Dangote Cement, BCG Analysis

Ammonia

Process flow for ammonia production with CO_2 emission streams.

1. CO_2 from breakdown methane in natural gas by steam and from combustion to produce heat

2. CO_2 is purged from the solvent to leave only hydrogen



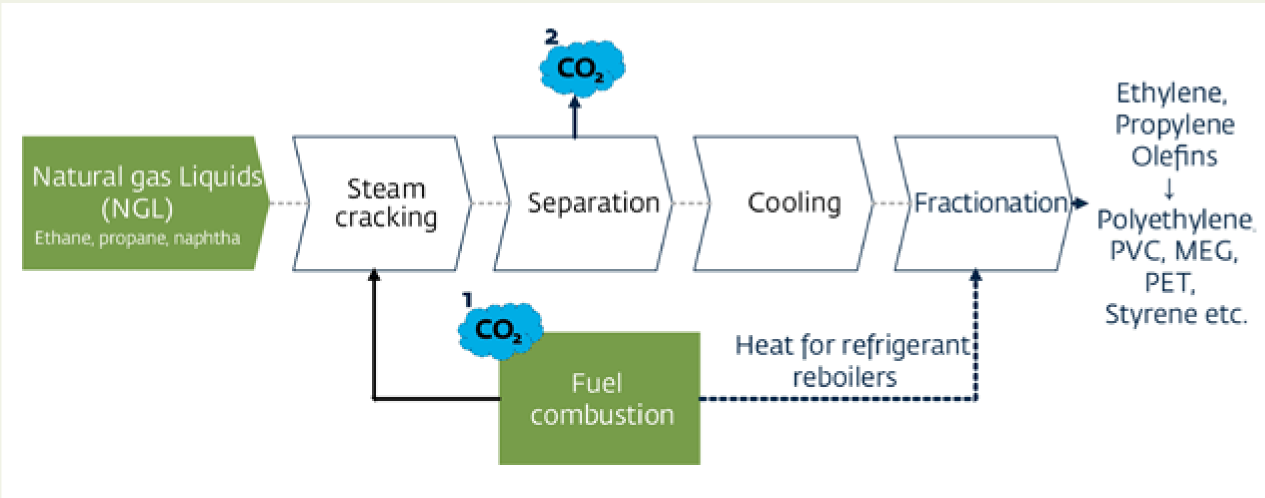
Source: Adapted from Indorama, BCG Analysis

Chemical Synthesis

Process flow for chemical synthesis with CO_2 emission streams.

1. CO_2 separated and expelled after breakdown of natural gas liquids by steam (steam cracking)

2. CO_2 generated from burning of fuel to produce heat for plant processes



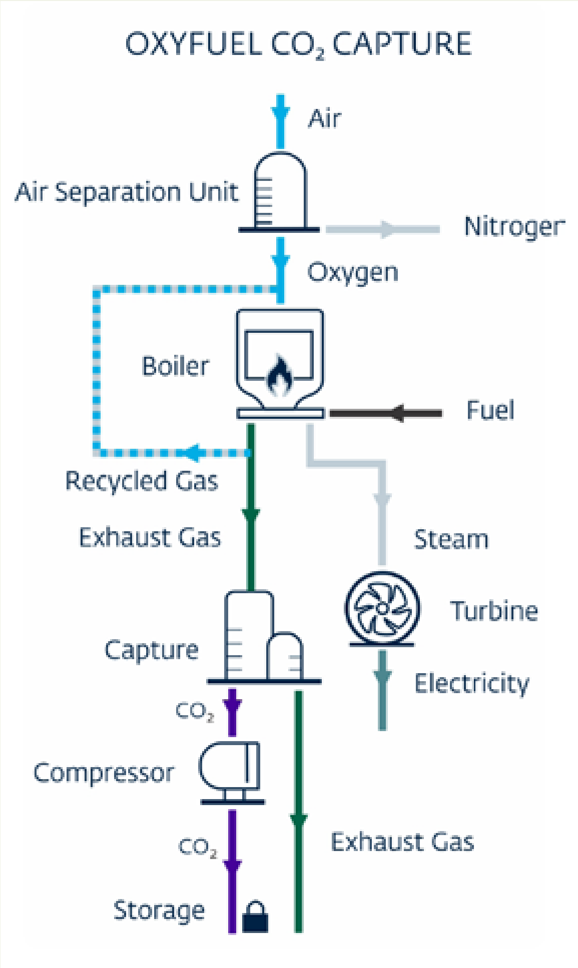
Source: BCG

3.3 Capture Technology Overview and Costs

From an economic perspective CO_2 capture technology (Box 3.2) has been a costly component of the CCS process and has hindered the development and advancement of CCS projects. However, heavy manufacturing (e.g. cement) are hard-to-abate industries which have limited options for emission reduction. CCS provides a viable method with which to tackle these emissions and therefore, for successful emission reduction, capture costs are an imperative consideration for success. The cost of CO_2 capture varies by industry, with a range of USD 15-25 per tonne, for producing pure CO_2 streams from ethanol or natural gas processing, to USD 40-120 per tonne for dilute CO_2 from heavy industry and power generation (IEA 2021b). The costliest capture process is direct air capture. This is an evolving technology, and current costs are high at USD 600-1000 per tonne of CO_2 (WEF 2023). It is estimated that this would need to fall below USD 200 per tonne to be adopted more widely (Azarabadi et al. 2023).

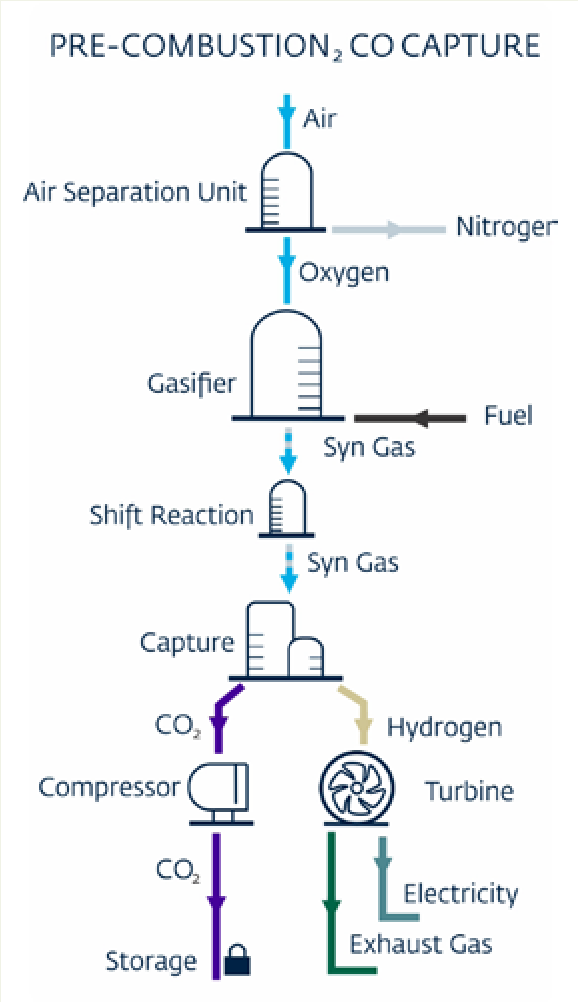
Box 3.2

CO_2 Capture and Technology Process

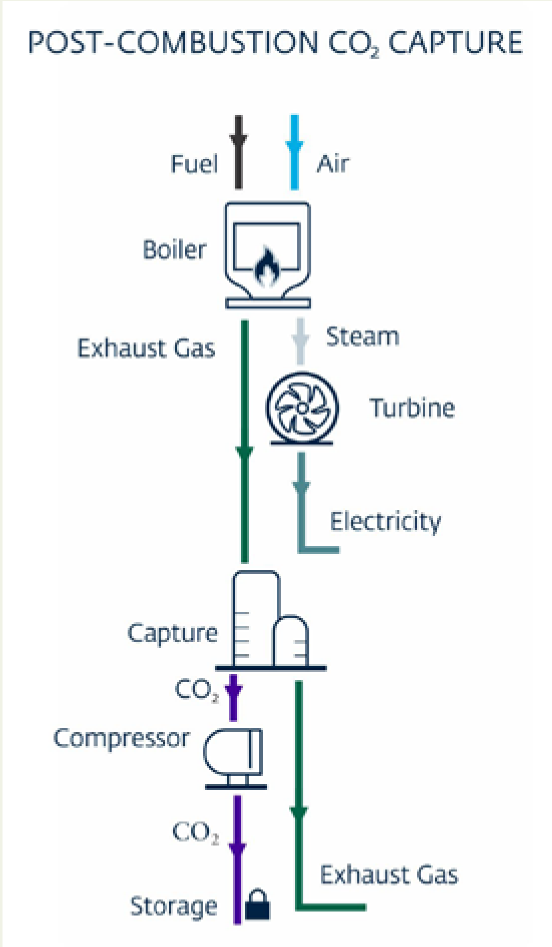


Oxyfuel combustion. This process burns the fossil fuel in pure oxygen rather than air. This produces exhaust gas that is mainly water vapour and CO_2.

Source: GCCSI 2024. © GCCS



Pre-combustion. This traps CO_2 before burning fossil fuel. The process converts fuel into a gaseous mixture of hydrogen and CO_2. The hydrogen can be used as a fuel.



Post-combustion. This process separates CO_2 after burning fossil fuel. CO_2 is captured using a liquid solvent or other separation method. This is most commonly used in power plants.

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4 CO_2 Transport in Nigeria

4.1 CO_2 Transport Options

CO_2 transportation is a key component of CCS and is the critical link between the CO_2 captured from an industrial facility and its storage in geological formations. Several different transportation options are available for consideration when planning a CCS project and the transportation method and distance have a significant impact on the overall cost. CO_2 can be transported in three states: gas, liquid and solid. However commercial-scale transport for CCS projects will use tanks, pipelines and/or ships for CO_2 in either a gaseous or liquid state. (Doctor et al. 2005, McKaskel et al. 2022).

To compile this chapter, data was sought from the Nigerian Upstream Petroleum Regulatory Commission (NUPRC) and the Nigerian Midstream and Downstream Petroleum Regulatory Authority (NMDPRA). This was bolstered with data from the public domain. The cooperation of both the NUPRC and NMDPRA to support this project is kindly acknowledged.

Pipeline

Pipelines are expected to be the dominant CO_2 transport method for large-scale projects, due to their ability to move large amounts of CO_2 economically. They have been an established method to transport CO_2 for over 40 years (primarily due to enhanced oil recovery (EOR). In addition, there are around 9000 kilometers of pipelines around the world operating today that have been used to transport CO_2 and other gases. Therefore, the method is well established and there is permitting and regulatory infrastructure in place in many areas.

Pipeline transport is done at high enough pressures to keep the CO_2 above critical pressure at all points in the pipeline systems (typical operating pressures are 83 to 152 bars) with a maximum inlet temperature of 48.9 °C, although temperature is often below this. This is higher than the pressure of natural gas transportation and, as a consequence, repurposing of gas pipelines for CO_2 may be limited. Re-purposing existing gas pipelines may be restricted to certain situations where there are limited transport capacities and shorter transport distances. There may also be an increase in cost with the addition of booster stations to operate re-purposed pipelines to the pressures necessary for CO_2 (McKaskel et al. 2022).

There are considerations on where to site pipelines but in general pipelines dedicated for CO_2 storage transport can be built in a very similar way to natural gas pipelines (McKaskel et al. 2022). An important aspect to consider is the risk posed by corrosion. Dry CO_2 (less than 60% relative humidity) presents a low risk to corrosion of pipelines made of carbon-manganese steel (steel alloy generally used for pipelines). However, if there is free water present and CO_2 cannot be dried adequately the pipelines must be made of a corrosion-resistant alloy such as stainless steel (Doctor et al. 2005). With respect to regulatory decisions on repurposing pipelines, DNV (Grotte et al. 2022) provide a comprehensive report on the possible regulatory options relating to repurposing natural gas pipelines. This report was focused on Europe but provides insight into the scope and processes needed to repurpose gas pipelines to other gases.

Ship

Transport of CO_2 by ship already occurs in many parts of the world, although not yet for CCS purposes. It is akin to the transport of liquified petroleum gas (LPG), where there is a significant amount of expertise and experience. Ship transport may be an economical solution for some locations, for example in transcontinental or intercontinental situations where suitable shipping waterways exist, and new pipelines are expensive to build. As with pipelines, the CO_2 must be transported in a specific state; in ships the CO_2 must be in liquid form. Here it is transported at a pressure of around 15 bars and a temperature of -28°C. For these properties the CO_2 needs more extensive dehydration and refrigeration than CO_2 designated for transport by pipelines (McKaskel et al. 2022). Whilst transportation by ship is a potential future option, more research and development is needed to ensure vessels are suitable for transporting CO_2 at such low pressures.

Truck and Rail

Transport of CO_2 by truck and rail is only possible for small quantities of CO_2 and these are most often used to move CO_2 locally around storage sites (GCCSI 2018). These transport modes are common for the food industry and other industries that use CO_2 in their operations. For truck transportation the load limit is around 16 metric tonnes and, due to the cost of transport materials and the emissions the transport itself releases, there is an economic cut off of around 320 km from source to hub/storage facility. For rail transport, rail cars can typically transport 73 tonnes of liquid CO_2 (according to the U.S. Department of Transportation specification of 105 rails cars) and have an economic travel distance of around 1600 km (NPC 2021).

4.2 CO_2 Transport Systems in Operation Around the World

CO_2 projects have successfully employed pipelines to transport CO_2 from capture point to storage for many years. CO_2 pipelines in the United States have been operating commercially since 1972, when the Canyon Reef pipeline was constructed in West Texas. Since then, the United States has constructed significant CO_2 pipeline infrastructure, mainly for EOR projects and industry. Most of these are below ground. In terms of above-ground pipelines, the U.S. DOE Illinois Basin-Decateur Demonstration Project uses a surface pipeline to transport CO_2 to the storage site at a rate of 0.33 Mt/yr. The Sleipner and Snøhvit projects in Norway use pipelines to pump CO_2 back from gas processing operations to be stored in formations under the North Sea. The Snøhvit pipeline was the world's first offshore CO_2 pipeline and is constructed from high-grade chromium steel to mitigate against corrosion from CO_2 in a super critical state (Hauber 2023). Oil pipelines are made from carbon steel and require external coatings to prevent corrosion. Gas pipelines are also made from carbon steel, although often flexible plastic pipes are used as well. Many CCS projects in development will use pipelines to transport CO_2, one of which is the UK's Northern Endurance Partnership. The Partnership will operate the end-to-end storage and transport system which serves the East Coast Cluster Project (decarbonization in the UK's Teesside and Humber region) and plans to develop onshore CO_2 pipelines to connect carbon emissions sites to offshore storage in the UK North Sea (EEC 2024).

The Northern Lights CCS project in Norway will be the first cross-border, open-source CO_2 transport and storage infrastructure network. This project will enable companies in Europe to store their CO_2 in geological formations under the Norwegian North Sea. The project will use ships to transport captured CO_2 to an onshore terminal and then onwards via pipelines out to the storage site. Operations are planned to start mid-2024 (Northern Lights 2024).

4.3 CO_2 Transport Options in Nigeria

Nigeria has CO_2 transport options which include pipelines, road, rail, and ship. For any CCS pilot project or full-scale CCS project, the type of transport selected will need to be most appropriate to the economics and logistics for both the site of the emissions source and the location of the CO_2 storage reservoir.

4.3.1 Pipeline

Nigeria has significant pipeline infrastructure already in place with more than 1000 kilometers of connected gas pipelines in the country (Adamu and Dama 2017). Much of this is used to transport natural gas from Kaduna, Warri and Port Harcourt around the country (Figure 4.1a). The pipelines are concentrated mainly in the Niger Delta region. These are close to many CO_2 emissions sources and near to hydrocarbon fields and the associated infrastructure and transport networks necessary to support the hydrocarbon industry (Figures 4.1b and 4.1c).

The infrastructure and facilities in the region range from basic oil and gas treatment and transportation to more modern modular designs which are gradually replacing ageing facilities, both onshore and offshore.

Pipeline networks in the Warri/ Escravos swamp area from the 1980s cover a wide range of gas pipeline infrastructure, injectors and offtakes, compression platforms (in swamps and shallow water) and onshore facilities including Warri Refinery, feeding the Delta Steel Plant. The idea behind these developments was to feed natural gas to local communities; there have been three major development phases during the past 40 years and the system is currently only partially effective. This network of pipelines will require a high degree of rehabilitation to enable the transport of CO_2. The Benin/ Sapele/ Warri region has seen some development of pipelines and gas plants, but progress was hindered due to lack of financial support, resulting in unusable gas compression and transport pipelines. These would require detailed inspection, rejuvenation and testing before being brought online to transport CO_2.

The current condition of each pipeline may indicate condensate intrusion and drop-out, water collection and consequent corrosion and metal loss. Pigging (using devices to perform pipeline maintenance operations) and other inspection tools would be valuable in defining the feasibility of each asset for CO_2 transport. Oil pipelines would require safe de-pressurization if in use, evacuation of product, flushing, cleaning, gauging and drying and then inspections as per gas pipelines.

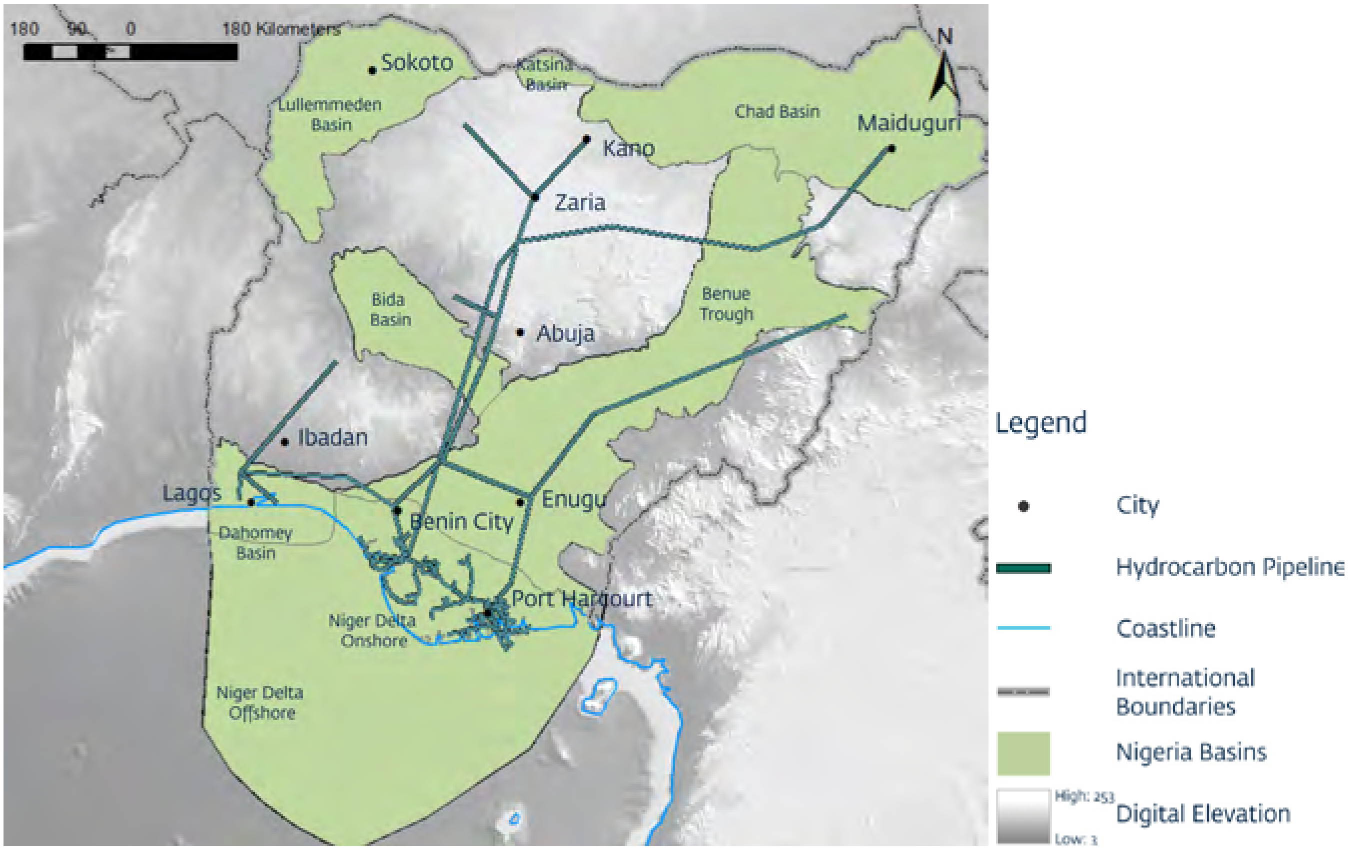
Key to the feasibility assessments are pipeline suitability, availability, adaptability, year of build, present usage, maintenance records and operability issues due to security conditions. Fortunately, most of the gas pipelines were designed to consistent codes and standards, and the conversion of pipelines to CO_2 usage is now matured globally, so learnings and synergies are freely available to support conversion in Nigeria.

There is arguably great value in studying and reworking gas plants which have stood idle for several years, many of which suffered during the Covid pandemic period. Gas treatment units and compressors could be adapted and replaced, and valving would need to be assessed for suitability of close-in and emergency shutdown. From a materials aspect, compressor seals and valve seatings would be replaced using suitable materials for CO_2 conditions. Controls systems would need to be refurbished and commissioned. SCADA (Supervisory Control and Data Acquisition) control and communications systems may be simple to adapt. Maintenance tools, spares, equipment, storage and transport are already in place for most recent operating pipelines.

Overall, pipeline repurposing will need to balance source and storage locations, facilities availability, adaptability and long-term operability.

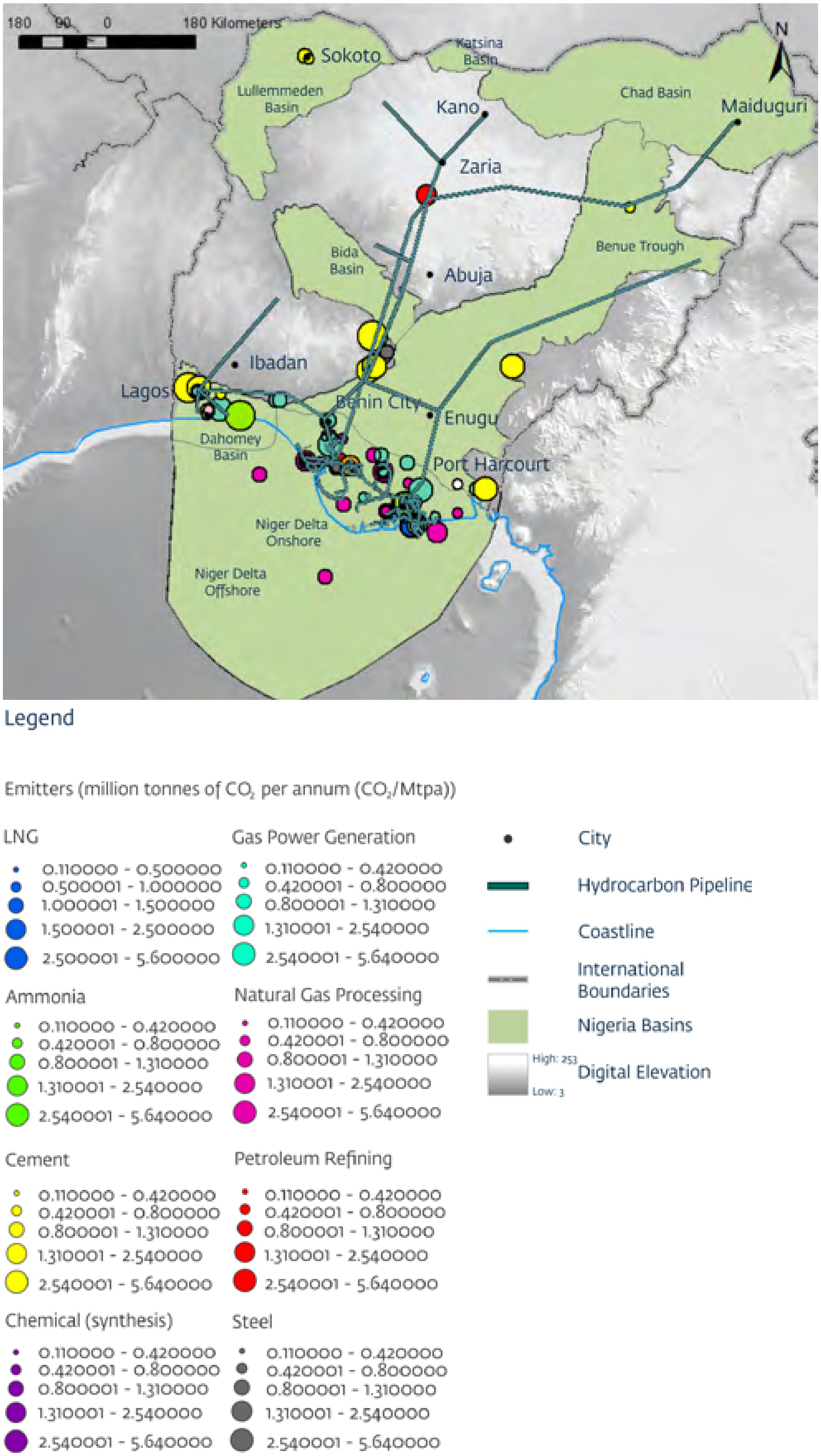
Note: repurposing of water pipelines has not been considered as very low pressures and community value issues may render this unfeasible.

Figure 4.1a. Pipeline networks in Nigeria.



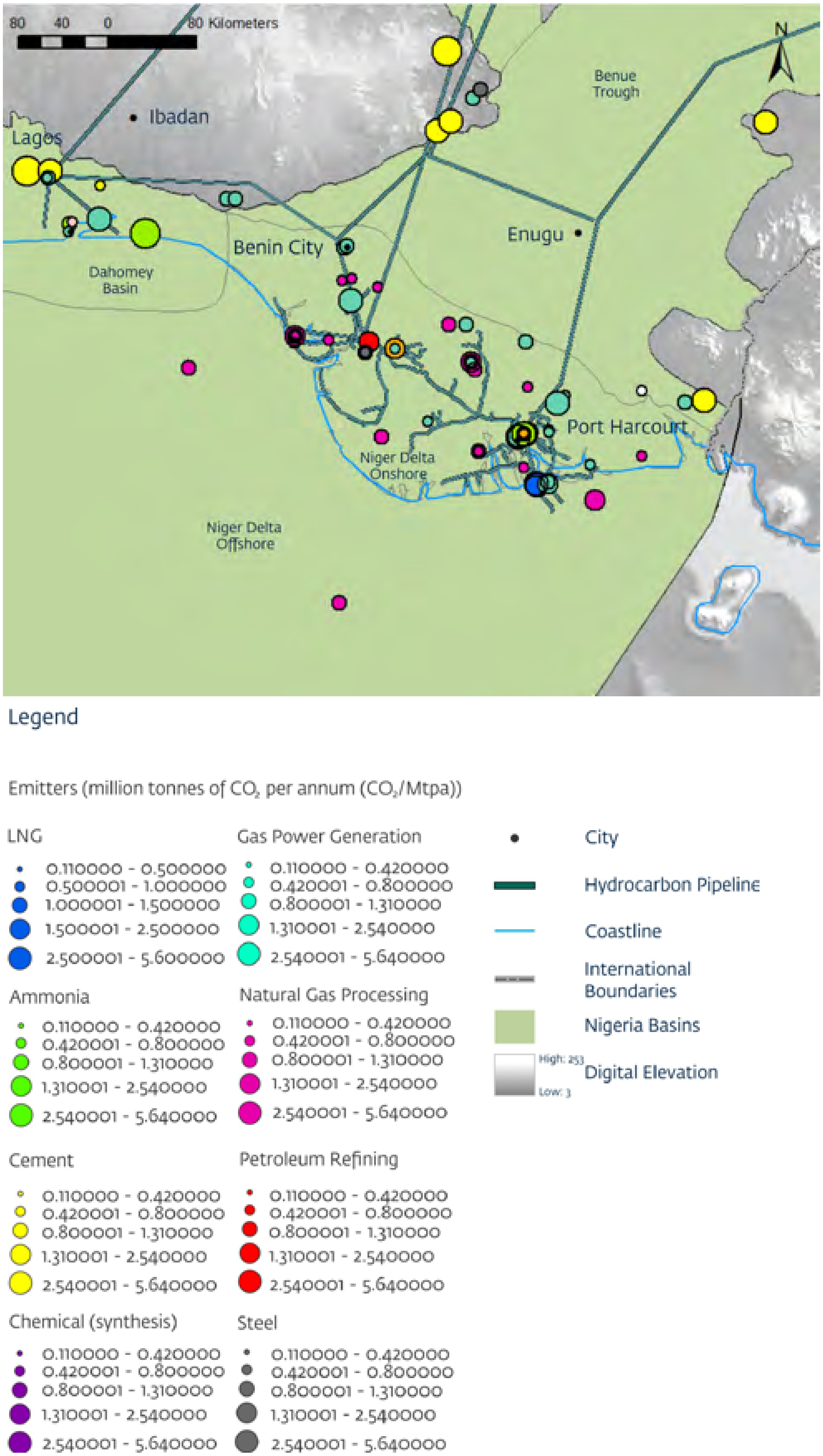
Source: Adeoti et al. 2015, Ambituuni et al. 2018, Halliburton.

Figure 4.1b. Pipeline networks and CO_2 emissions sources by emitter sector in Nigeria.



Source: Adeoti, et al. 2015, Ambituuni et al. 2018, BCG, Halliburton.

Figure 4.1c. Pipeline networks and CO_2 emissions sources in the Niger Delta region.

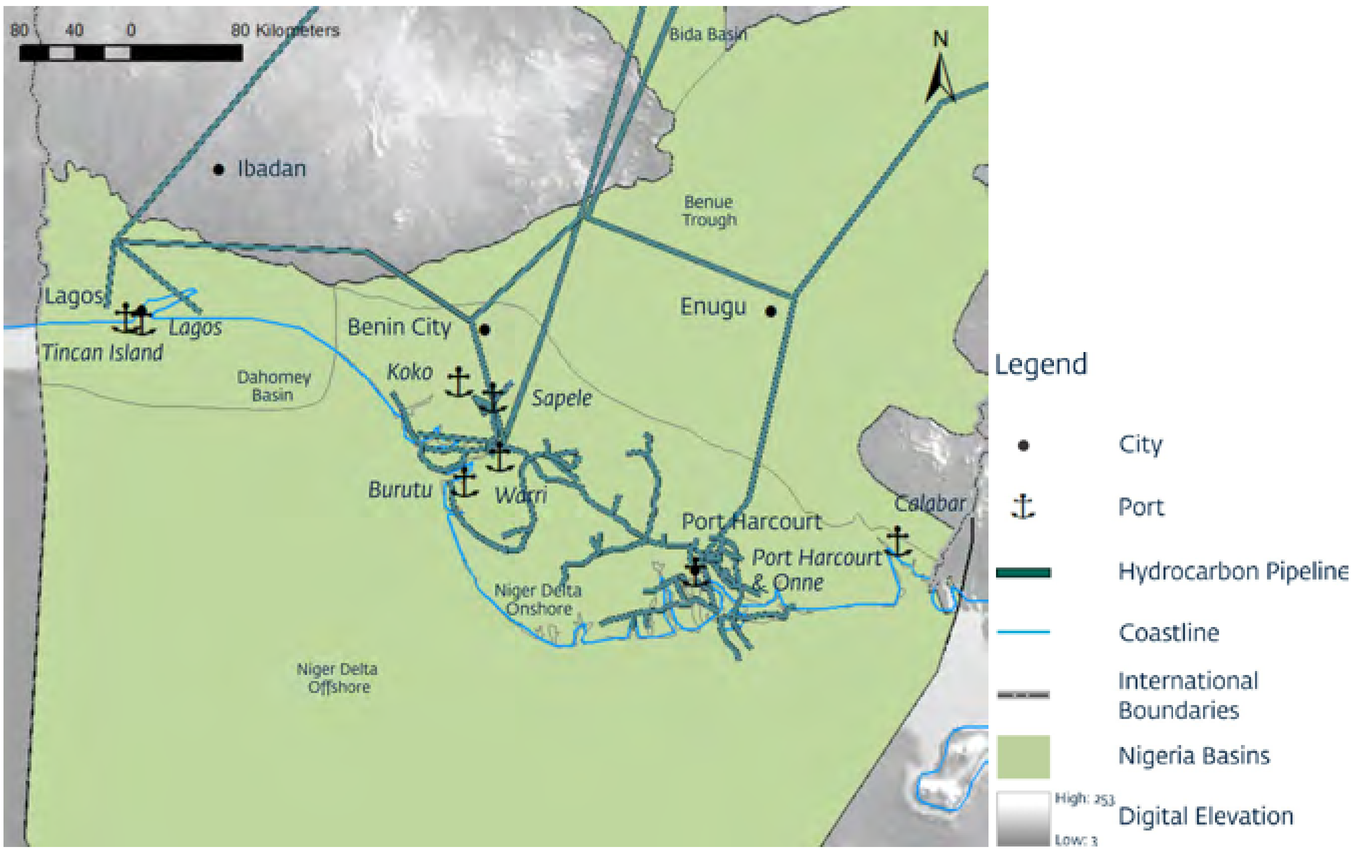


Source: Adeoti et al. 2015, Ambituuni et al. 2018, BCG, Halliburton.

4.3.2 Ship

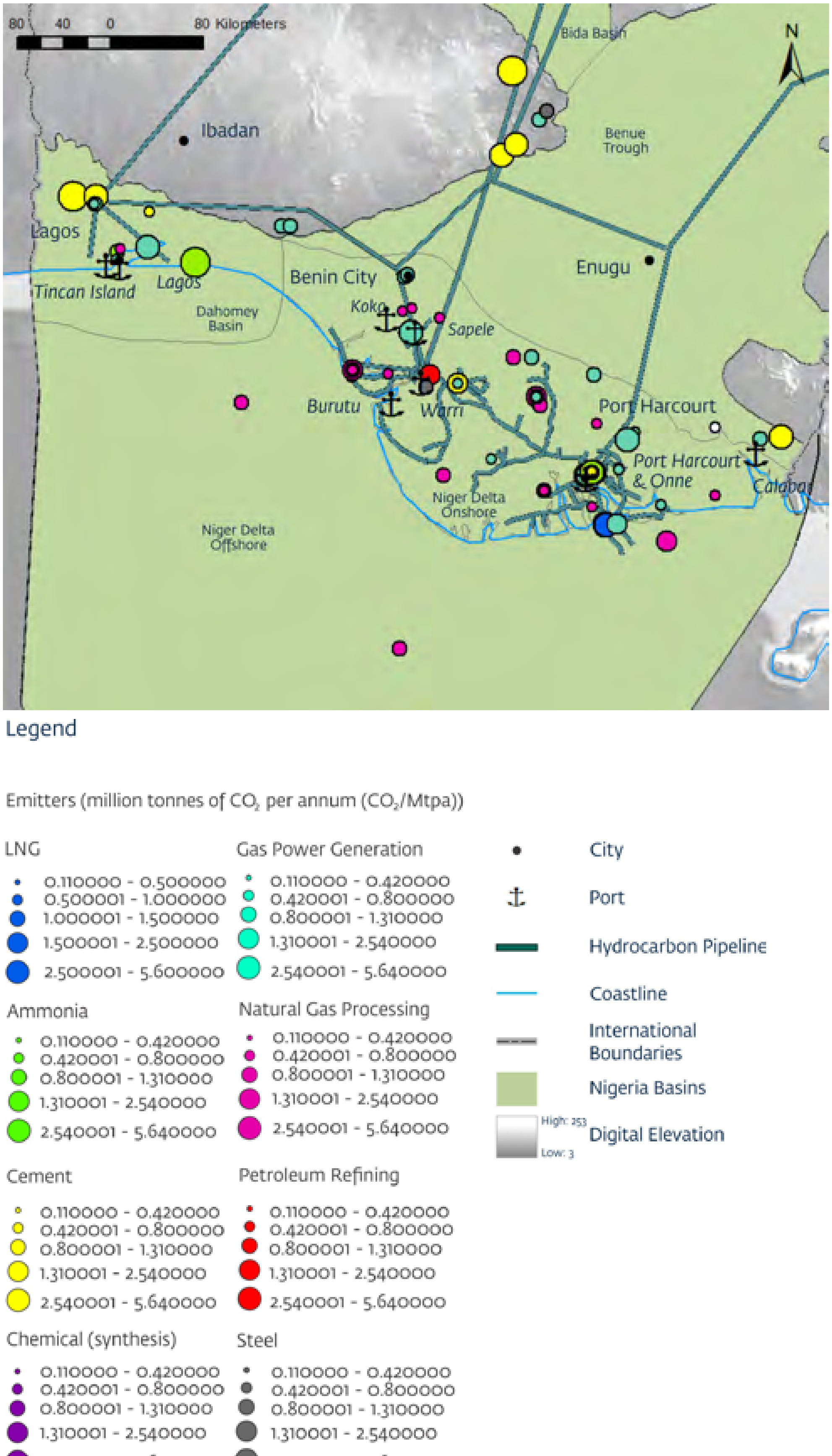
Nigeria has several major ports along its coastline which are equipped to handle the transport of hydrocarbons from offshore fields (Figure 4.2a). The ports of Lagos, Calabar, Onne and Port Harcourt already handle crude oil and petroleum products. The delta ports of Kokos, Burutu, Sapele and Warri provide shorter distances for haulage of cargo from some of the inland states such as Anambra, Imo, Enugu, Delta, Edo, Kogi, Ondo, Benue (Nigerian Ports Authority). Some of these states are also traversed by the Niger River which could be investigated as a shipping route for CO_2 captured from emissions sources further inland (Figure 4.2b). CO_2 can be transported long distances by ship, for example the Northern Lights project plans to transport CO_2 by ship from the Netherlands to Øygarden in the Norwegian North Sea (Total Energies).

Figure 4.2a. Major ports in Nigeria.



Source: Adeoti et al. 2015, Ambituuni et al. 2018, World Bank 2017a, Halliburton.

Figure 4.2b. Major ports in Nigeria and CO_2 emissions sources by emitter sector.

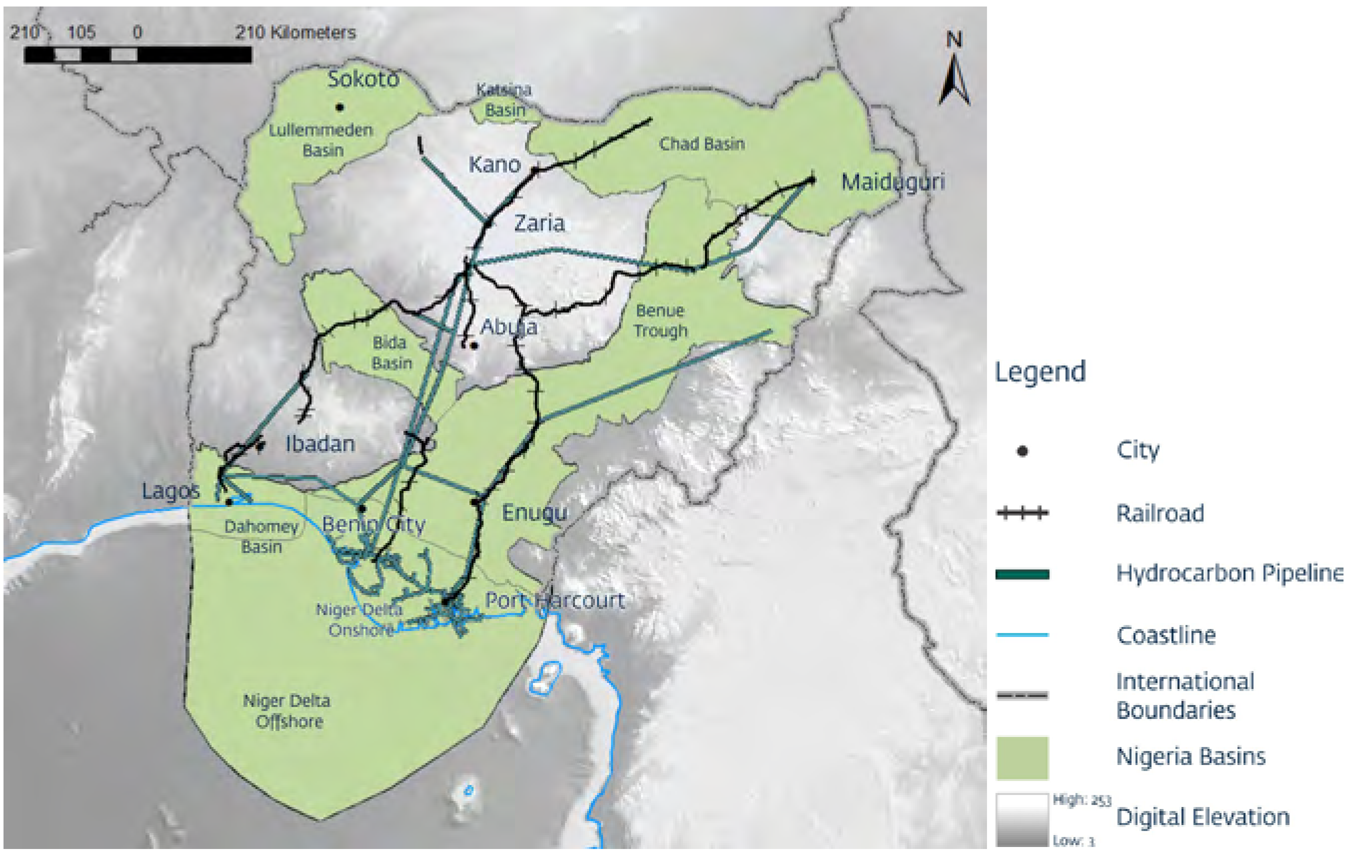


Source: Adeoti et al. 2015, Ambituuni et al. 2018, World Bank 2017a, BCG, Halliburton.

4.3.3 Rail

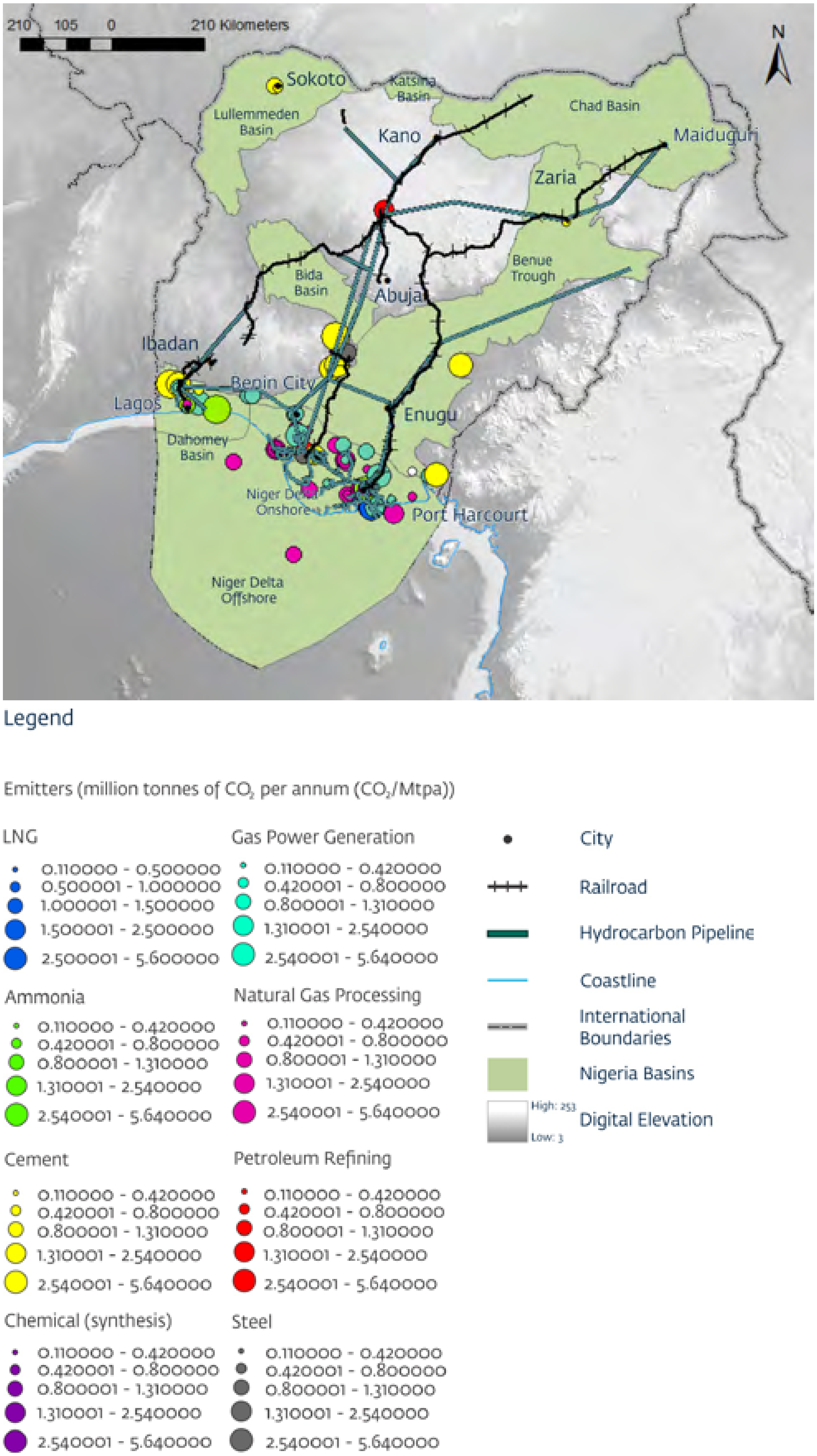
Even though the quantities would be relatively small in comparison to movement by pipeline, the railway networks in Nigeria (Figure 4.3a) run close to many CO_2 emissions sources. Figure 4.3b shows the proximity of these sources to a railway. For some far outlying sources, railway networks may be the only viable way to transport CO_2. However, the location of the corresponding CO_2 storage reservoir would need to be within 1600 kilometers of the source to ensure that the distribution of CO_2 remained economically viable.

Figure 4.3a. Railroad networks in Nigeria.



Source: Adeoti et al. 2015, Ambituuni et al. 2018 Humanitarian Data Exchange 2024, Halliburton.

Figure 4.3b. Railroad networks and CO_2 emissions sources by emitter sector.

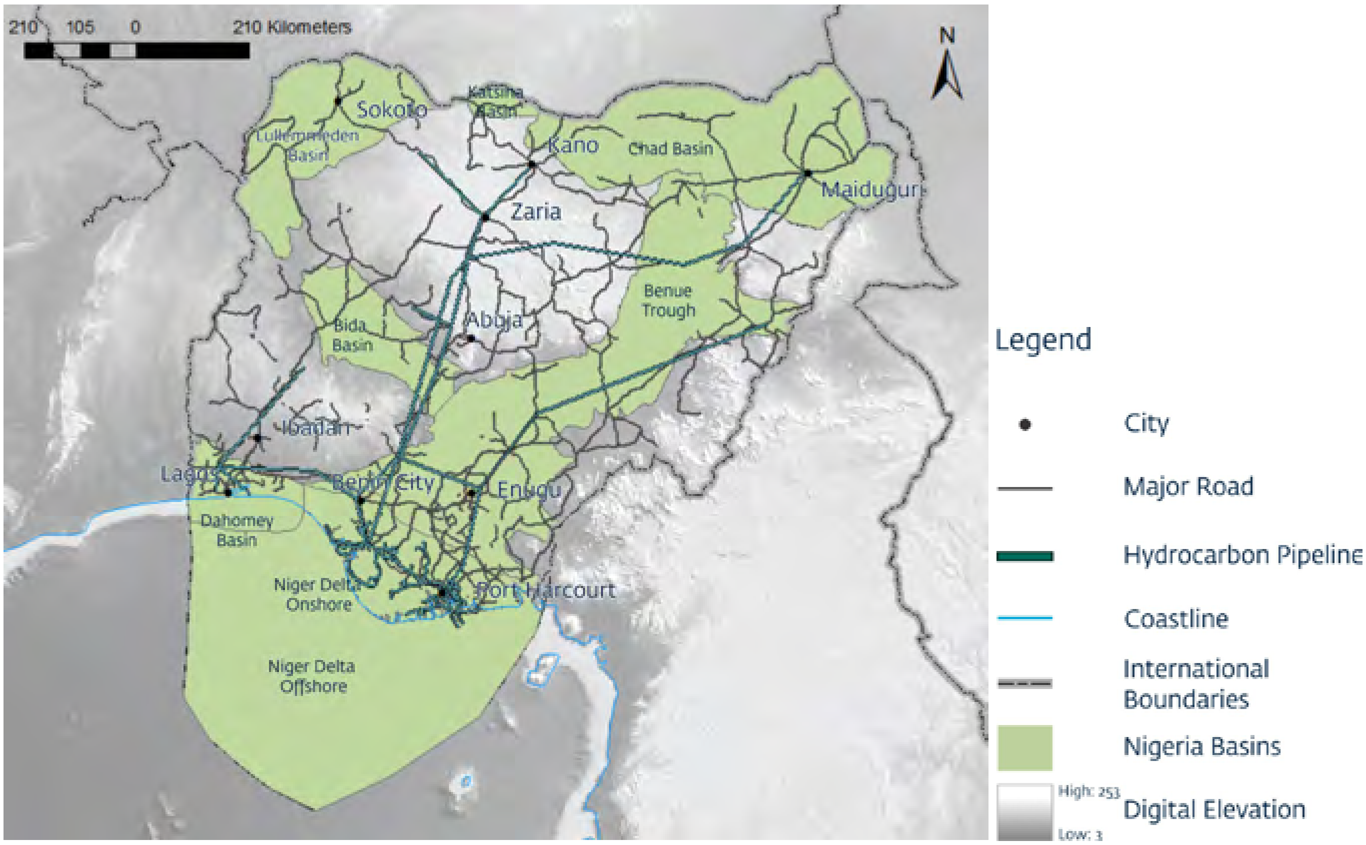


Source: Adeoti et al. 2015, Ambituuni et al. 2018, Humanitarian Data Exchange 2024, Halliburton.

4.3.4 Road

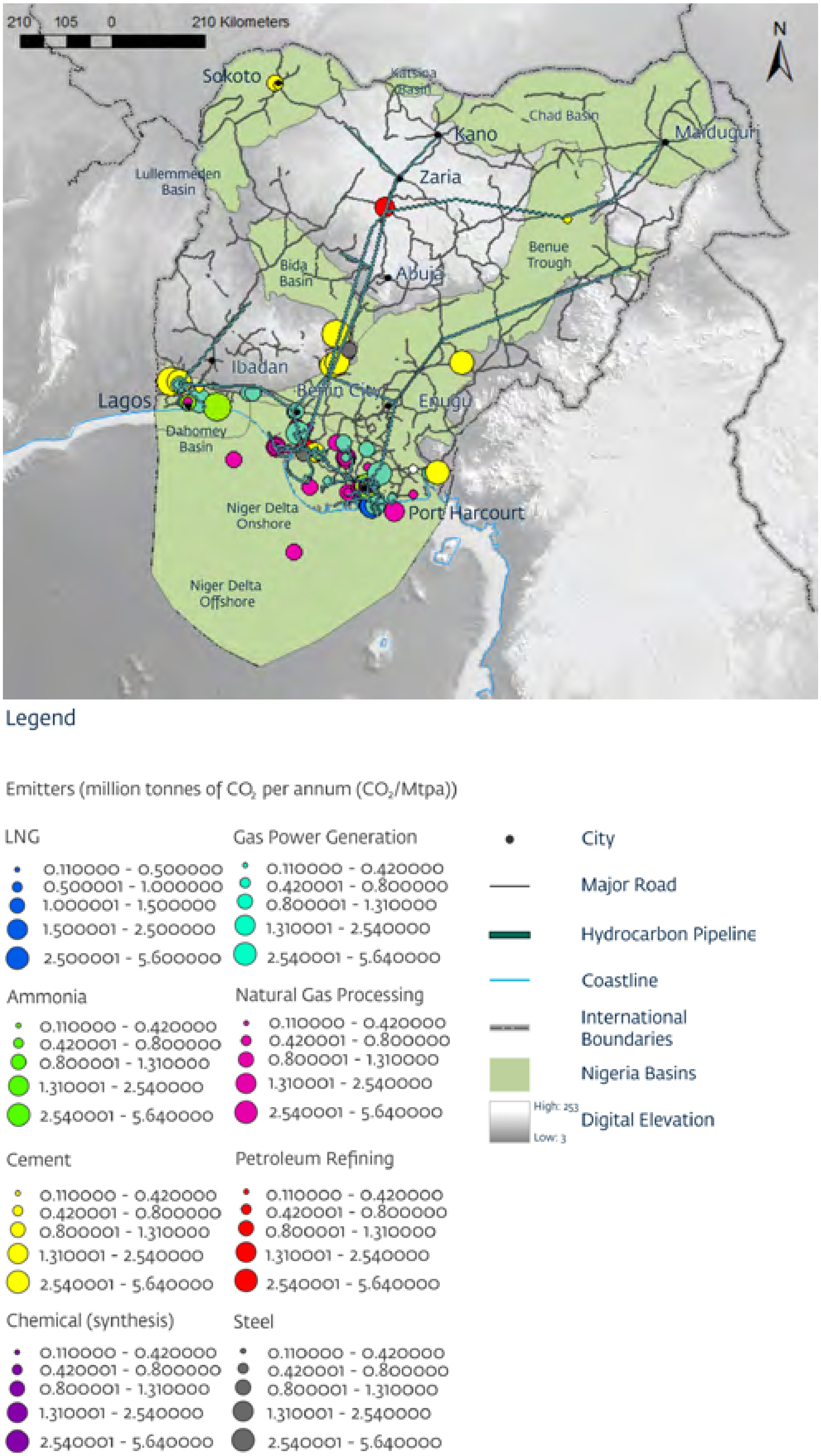
Transportation of CO_2 by road in Nigeria will likely be confined to short distances due to the diseconomy of scale of transporting small volumes and the trade-off between emissions created by the transport of CO_2 and the CO_2 captured. However, road networks exist throughout Nigeria (Figure 4.4a) and link to emissions sources (Figure4.4b) in remote areas. Therefore, the transport of CO_2 by road may be possible for small-scale projects, or to provide a method of transporting CO_2 to larger holding facilities before onward transport via more economical means such as ships and pipelines.

Figure 4.4a. Road networks in Nigeria.



Source: Adeoti et al. 2015, Ambituuni et al. 2018, World Bank 2017b, Halliburton.

Figure 4.4b. Road networks and CO_2 emissions sources by emitter sector in Nigeria.

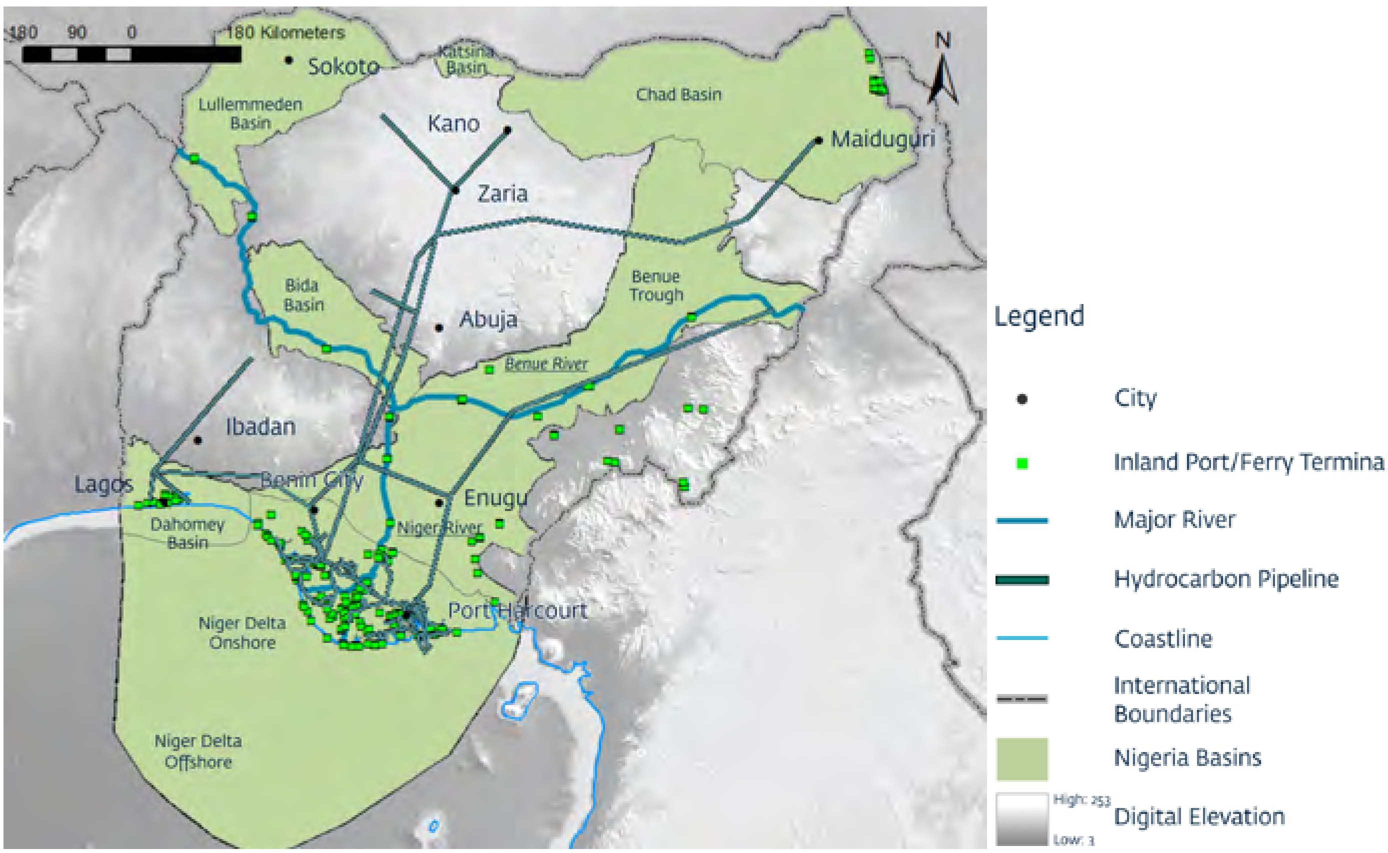


Source: Adeoti et al. 2015, Ambituuni et al. 2018, World Bank 2017b, Halliburton.

4.3.5 Inland Waterways

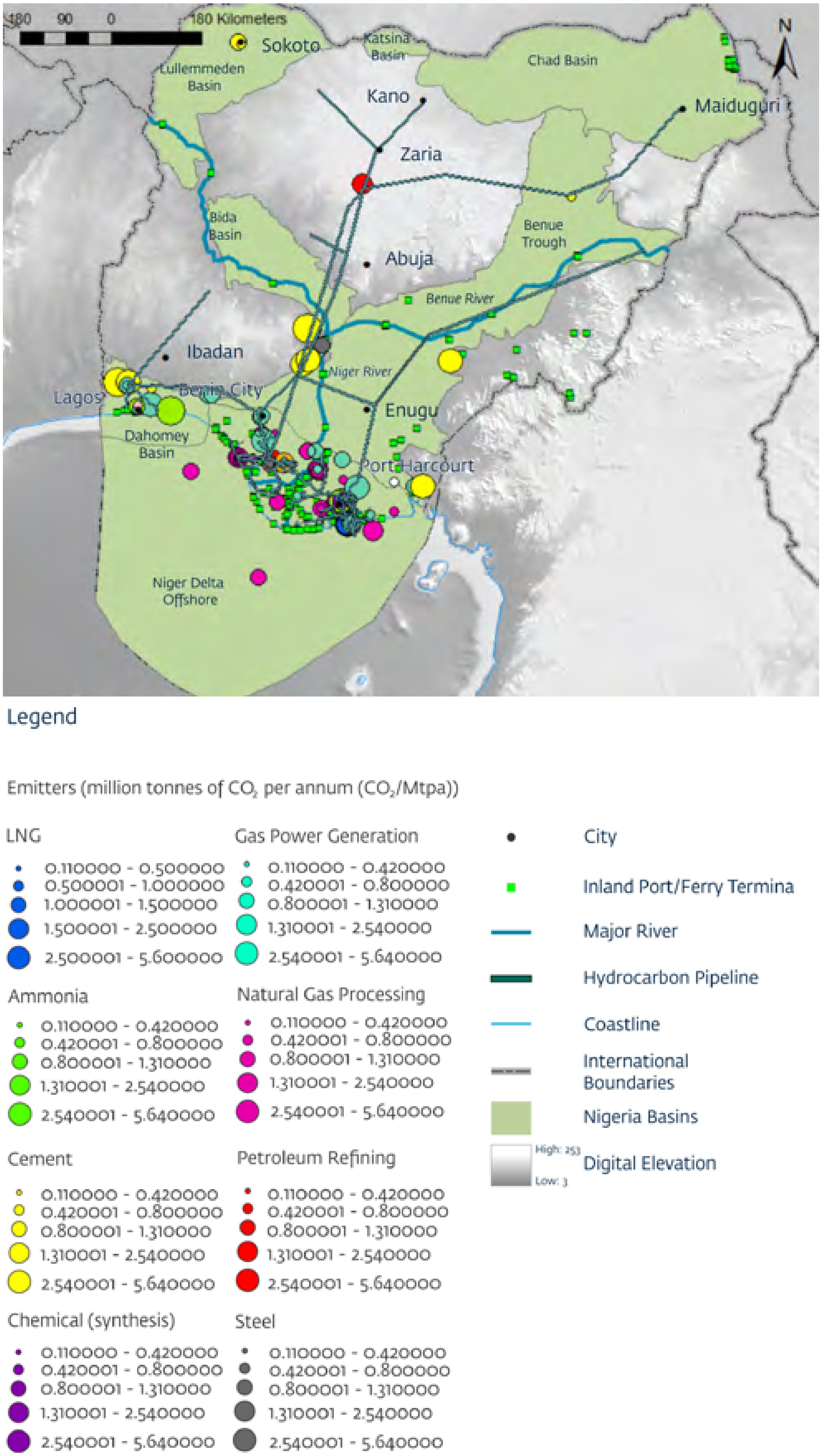
The transportation of CO_2 via inland waterways may be an interesting option to consider for reaching areas in Nigeria which are remote from pipelines. The Niger and Benue rivers are major water courses with numerous ports expanding into the east and west of Nigeria (Figure 4.5a). Both are used by commercial shipping and the Benue River is also a valued transportation route for petroleum distribution. However, the extent to which boats can navigate these rivers during the year is limited. Some areas such as the route from the Atlantic Ocean to Onitsha on the Niger River is navigable all year round, whereas other areas on both rivers will reduce in depth due to seasonal weather. This will limit the type and size of vessel that could transport CO_2 from emissions sources (Figure 4.5b).

Figure 4.5a. Major river and inland ports in Nigeria.



Source: Adeoti et al. 2015, Ambituuni et al. 2018, Humanitarian Data Project 2018, Halliburton.

Figure 4.5b. Major river and inland ports and CO_2 emissions sources by emitter sector in Nigeria.



Source: Adeoti et al. 2015, Ambituuni et al. 2018, Humanitarian Data Project 2018, Halliburton.

4.4 Implications of Nigeria's Transport Networks for Future CCS Development

Nigeria has a number of different transport options for moving CO_2 from a place of capture to dedicated storage. The most favorable option is pipeline due to the large amounts of CO_2 that can be transported. These pipelines are concentrated in the Niger Delta region where there is also a significant amount of industrial activity creating CO_2 emissions. However, Nigeria has a number of emissions sources throughout the country that are far from pipelines. Alternative options for transport would need to be considered for these areas if pipeline infrastructure was unable to be developed there. Future CCS development in terms of linking up feasible transport networks and emission sites would need to place strategic value on the economics of either repurposing existing pipelines or rebuilding new ones. Consideration could also be placed on the possibility of creating hubs and clusters that can facilitate moving CO_2 by a method of transport other than pipeline, over distances that are economically viable to hubs. From these hubs higher volumes of CO_2 can then be transported to the storage resource via pipeline for injection. Large scale deployment of CCS will most likely rely on ships and pipeline transport for hubs and clusters (e.g. Northern Lights, Norway) However, for small scale pilot projects this should not rule out other forms of transport in order to help initiate these projects and in turn encourage the growth of a CCS industry in Nigeria. In terms of major targets for decarbonisation, cement accounts for a large share of Nigeria's emissions from industrial sources. A key consideration for CCS projects with the cement sector is its proximity to transport options for transport of CO_2 to geological storage sites. The Niger Delta area holds both the greatest density of pipeline networks and the most optimal geological storage formations (Chapter 6). Therefore, transport of CO_2 may need to cover longer distances in order to reach suitable geological storage sites. Nigeria's main cement manufacturing areas are a few hundred kilometers from the Niger Delta. A pipeline does run close to some of the cement sites towards the center of the country but if this was not a feasible option then other forms of transport do exist in this area. Transport by rail and ship are possible providing the volumes transported and distance to storage sites remain logistically and economically feasible. Economic limits for transport by rail are up to 73 tonnes of liquid CO_2 for distances up to 1600km. The distance from some cement sites to the Niger Delta are a few hundred kilometers – well within the feasible rail transport distance. Transport of Liquefied Natural Gas (LNG) by ship is already common places and in addition long distance transport of CO_2 by ship is planned for the Northern Lights project. Experience from both of these activities could be leveraged to look at CO_2 transport along Nigeria's major waterways. Petroleum is already transported to the interior of the country via its major rivers, hence this method of transportation for CO_2 could also be supported if facilities to cater for large boats already exist.

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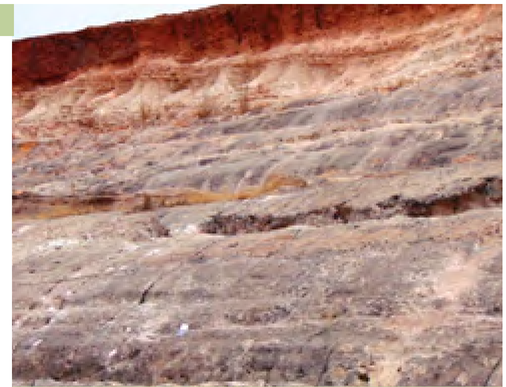
5 Geological Storage of CO_2



5.1 Overview of CO_2 Storage

The storage component is the final stage in the CCS value chain. CO_2, once captured, can be stored in geological formations and has been done so for decades (GCCSI 2018). The geological formations that are suitable for CO_2 storage exhibit much the same characteristics as those which have naturally occurring hydrocarbons. However, there are some differences which are described in section 5.2.

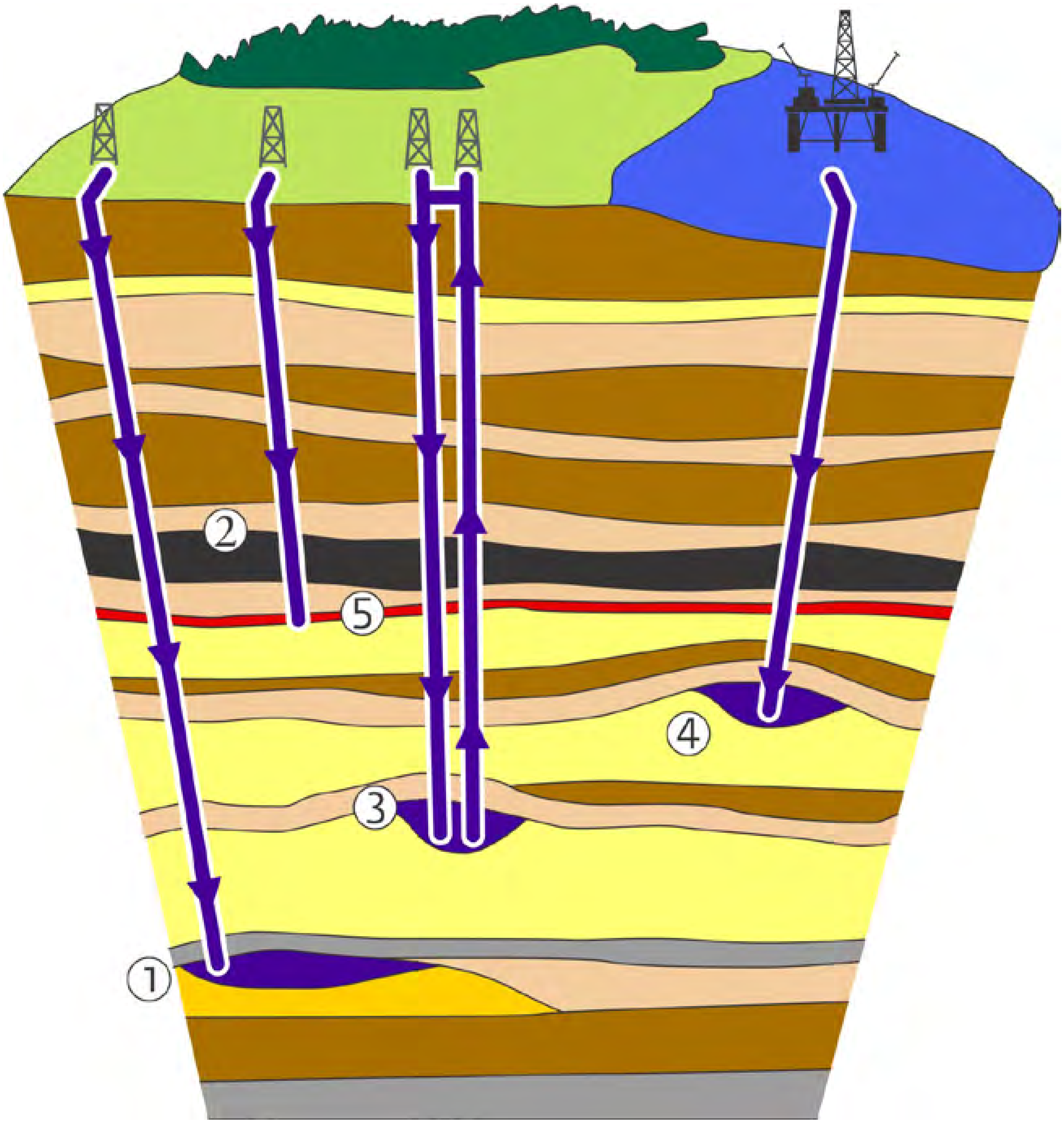
The types of geological resources that make good storage reservoirs, and which are the most commercially viable solutions today, are found in deep saline aquifers and depleted oil and gas fields (Figure 5.1). These storage reservoirs are located in sedimentary basins and capable of trapping injected CO_2 for many centuries via a number of mechanisms (Box 5.1). Deep saline aquifers are water bearing formations that have geological properties suitable for storing CO_2 (such as sandstones or carbonates that exhibit suitable porosity and permeability) and an effective barrier to upward migration of the CO_2 (e.g. a very low permeability cap rock such as shales and/or salts).

Saline aquifers are widely distributed across the world, with many located close to emission sources, and can present a very large storage capacity with some estimates up to 10,000 gigatonnes (Gt) (IEA, 2008). They are, however, relatively under-explored compared to depleted oil and gas fields and therefore, carry a greater degree of uncertainty on suitability for the injection and storage of CO_2. In contrast, they have limited drilling activity which can mean less risk to potential leaking of CO_2 through any legacy wells.

Depleted oil and gas fields, in comparison, are well explored and it is therefore easier to understand the characteristics of the subsurface for storage of CO_2 but also the likely capacity based on historical oil and gas volumes. Depleted oil and gas fields do however, present some challenges. Legacy wells at these sites can present a vulnerability to leakage if they are not properly plugged. In addition, adjacent operations to the storage site can be at risk of pressure changes from injected CO_2 (Hannis et al. 2017).

Both saline aquifer and depleted oil and gas fields are being used today across several projects, although the current trend in areas such as North America and the North Sea is to favour saline aquifers (GCCSI, 2022). Alternative geological storage options, though much less studied and utilized, can found in basalt formations and non-mineable coal seams. These are described in section 6.10.

Figure 5.1. Geological Storage options for CO_2. 1- Saline Aquifers, 2- Unminable coal seams, 3- CO_2 for Enhanced Oil Recovery, 4 – Depleted oil and gas fields, 5- Basalt.



Source: Modified from GCCSI

Box 5.1

Principles of CO_2 Trapping and Migration and the Effects of Pressure and Depth on CO_2 State

The way CO_2 moves through the reservoir, the mechanisms that traps it and the physical state it is in a storage unit are all subtly interlinked processes. Figure 5.2 shows these processes and how and where they operate in the subsurface.

CO_2 Trapping Mechanisms

CO_2 is trapped by several mechanisms in the subsurface after injection. Each of these mechanisms works on different time and size scales. The trapping style and the scale can be seen on the center of the diagram, and beneath that is the time scale that each trapping mechanisms works over.

Moving from left to right, each trapping mechanism in turn equates to increasing security of the CO_2 remaining trapped in the reservoir.

- Structural and stratigraphic trapping: buoyant CO_2 is trapped underneath an impermeable seal in structural or stratigraphic traps.
- Residual: CO_2 is trapped via capillary pressure in small pore spaces in the storage reservoir.
- Solubility trapping: dissolution or solubility is a trapping mechanism where CO_2 is dissolved in the formation waters.
- Mineral trapping: mineral trapping whereby the dissolved CO_2 is precipitated as carbonates.

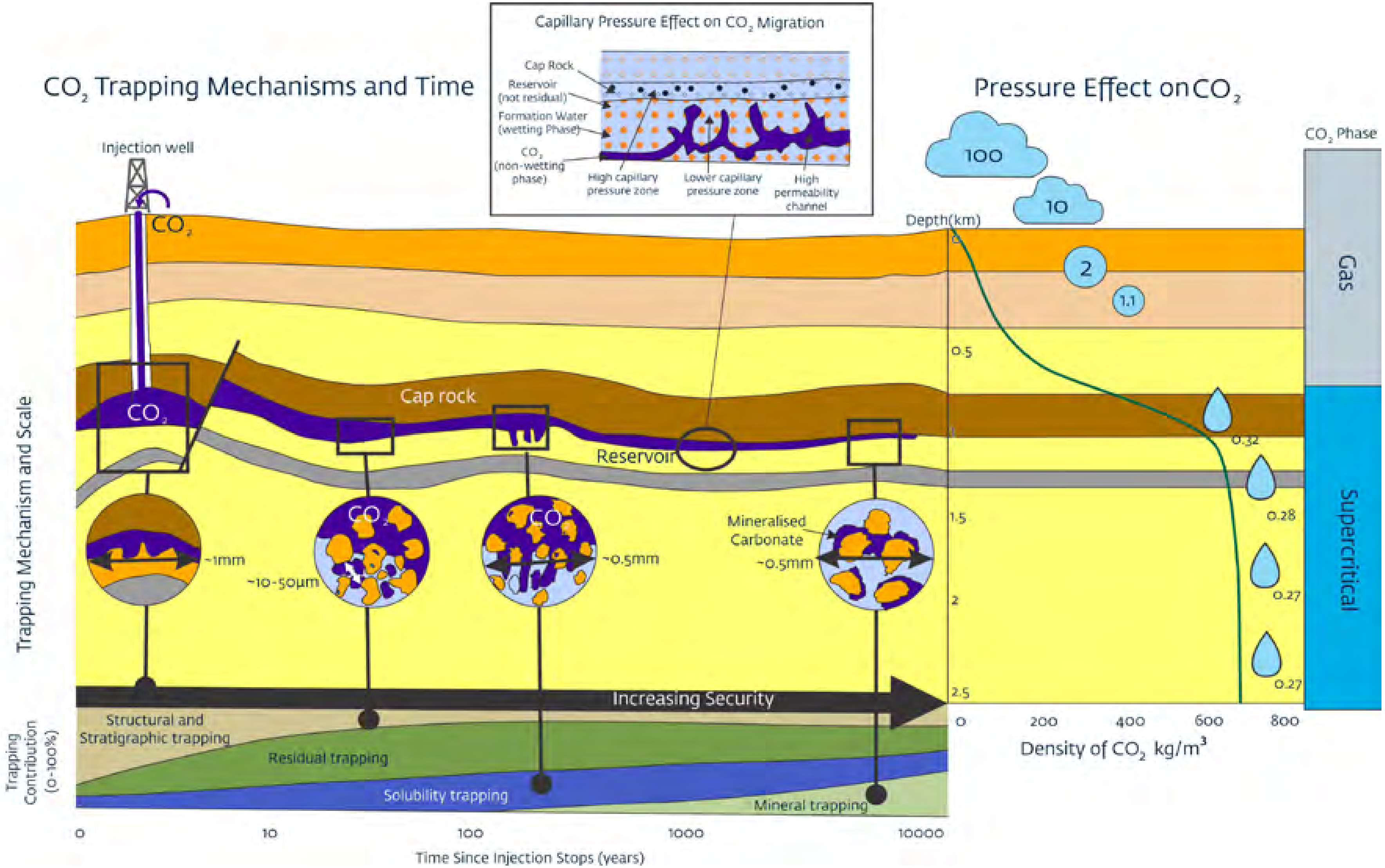
CO_2 Physical State and the Effect of Pressure and Depth

CO_2 is preferably injected in a supercritical phase. In this phase it will behave as a gas but has the density of a fluid (Bachu, 2003) and is less buoyant. Therefore, CO_2 will migrate more slowly (compared to CO_2 gas) and have a greater chance of being retained. In addition, the increased density of supercritical CO_2 results in an increased mass of CO_2 stored compared to CO_2 gas. The right-hand side of the diagram shows how CO_2 transitions from a gas to supercritical state (>800 m) with pressure changes, it also shows how the density of CO_2 changes with pressure from 100 kg/m^3 in the atmosphere to around 0.32 kg/m^3 at the 800 m depth mark.

The Forces that Operate to Move CO_2 Through the Reservoir

When CO_2 is moving through the pore space of the rocks (after reaching hydrostatic pressure) there are key variables that affect its movement or immobility, one of the most important being capillary entry pressure. This is the pressure that the CO_2 must overcome to displace the brine water held by capillary forces in the pores of the sediment. Capillary pressure (the pressure of the non-wetting CO_2 phase) is a function of the pore radius, the wettability (the contact angle of the fluids with the rocks) and the interfacial tension of the fluids. The process is complex; however, the reservoir and seal rocks of a storage unit will exhibit certain ranges of these properties and its these that will govern how fast or slow CO_2 moves, but also how well it remains contained under the seal (Bikkina et al. 2018, Espinoza and Santamarina 2017).

Figure 5.2. Schematic diagram to show CO_2 trapping mechanisms, the effects of pressure and depth on CO_2 phase and the process by which CO_2 migrates through reservoir rocks.



Source: Modified from IPCC 2005, GCCSI 2022, Alcade et al. 2018, CO_2CRC 2015

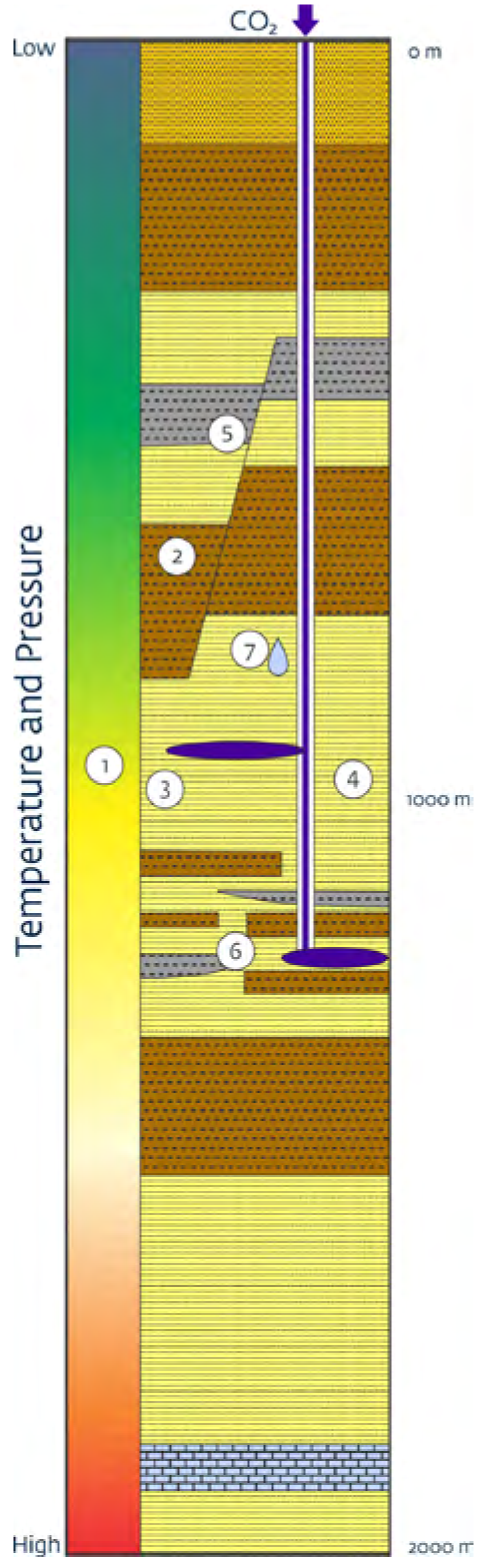
5.2 Geological Properties and CO_2 Storage Best Practice

5.2.1 Geological Properties for CO_2 Storage

To ensure that CO_2 can be both injected and stored in the subsurface effectively and safely, a key set of geological criteria must be met. Whilst many of these criteria are the same as those pertinent to conventional hydrocarbon resources, there are some distinct characteristics particular to CO_2 storage viability. The following geological characteristics are key for CO_2 storage (numbering below corresponds to numbering shown on Figure 5.3).

1. Depth and Temperature: temperature and pressure (Box 5.1) will determine whether injected CO_2 will act as a supercritical fluid. CO_2 in a supercritical phase will behave as a gas but has the density of a fluid (Bachu, 2003) and is less buoyant. For CO_2 to behave as a supercritical fluid, temperature must exceed 31.1°C and pressures should be greater than 7.38 MPa (Bachu 2003). For this reason, cold sedimentary basins with low temperature gradients are favorable because CO_2 will retain a higher density at shallower depths (Bachu, 2003). A pressure of 7.38 MPa is equivalent to approximately 800 m depth in a hydrostatically pressured basin. CO_2 trapping (Box 5.1) by dissolution can be increased in basins with higher temperatures and pressures (Tang et al. 2019).
2. Seal Quality: evaporites and very low permeability shales are ideal cap rocks or seals for containing CO_2. Evaporites present the optimal seal characteristics, whilst shales perform well without needing to be mineralogically mature. Seal degradation through erosion, stratigraphic thinning and faults present risks to containment.
3. Reservoir Thickness: reservoir thickness ideally needs to be greater than 50 m. Evidence from several storage projects has demonstrated that the ideal thickness is between 100-200 m which, when combined with a permeability range of around 3000 millidarcies creates greater injectivity potential (GCCSI 2022). However, in some projects thinner reservoirs are being used.
4. Porosity and Permeability: an ideal porosity for the reservoir is over 20%, with a range between 10-20% being acceptable. Once under 10% the storage formation is challenged with respect to CO_2 injection and migration (Callas et al. 2022). Based on existing projects and test data, the optimal permeability of the reservoir formation appears to be around 3000 millidarcies. However, a high permeability reservoir is not necessarily always optimal since high permeability will result in faster plume migration. Some storage projects may, therefore, benefit from lower permeability formations (GCCSI, 2022).

Figure 5.3. Principle geological properties for a CO_2 storage site



5. Faults: faulting in a CO_2 reservoir can compromise the sealing ability of the caprock if the faults are prone to leakage. Faults in regions where there is ongoing tectonic activity can also be prone to movement which could affect the reservoir's stability and therefore containment of CO_2.

6. Reservoir Heterogeneity: geological formations are rarely truly homogenous and some degree of rock heterogeneity in CO_2 reservoirs will generally be present. The way CO_2 moves through formations is strongly controlled by the pore size of the rocks in the reservoir (Box 5.1). Therefore, the presence of heterogeneity in a storage formation can affect a number of aspects. These are the speed of vertical and lateral migration (Krishnamurthy et al., 2020), the speed of CO_2 dissolution (Honjun et al. 2010), the capacity of the reservoir, the injection rate stability (Khudiada et al., 2020) and the pressure in the reservoir from the increase in fluid volume (i.e. injected CO_2) (Rasheed 2020).

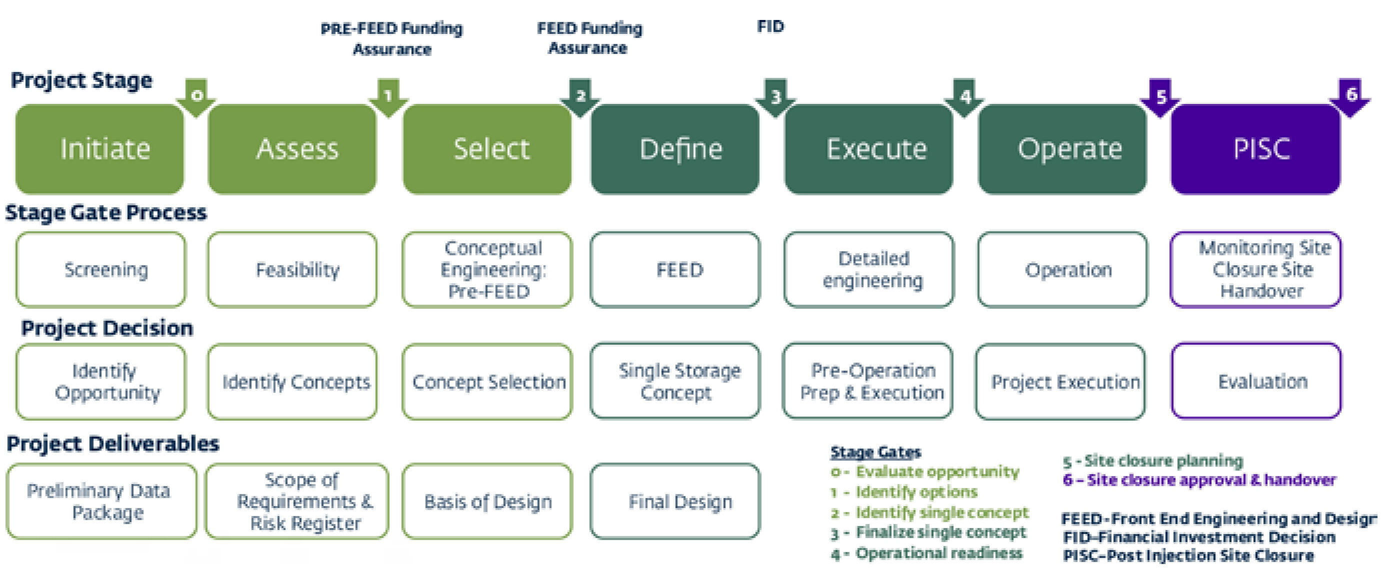
7. Formation water salinity: the salinity of formation waters can affect CO_2 solubility, which in turn can affect the rate of dissolution (Zhang et al. 2017). High salinity levels also affect salt precipitation that consequently may affect the injectivity of CO_2 through a reduction in porosity and permeability. This can lead to pressure build-up in the reservoir (Cui et al. 2023).

5.2.2 Best Practice Principles for CO_2 Storage Site Selection

The best practice approach to CO_2 storage projects is a detailed and extensive process that follows many stages and uses several areas of expertise and technology disciplines to fulfill each requirement. The details of a best practice process may also change according to the storage site type, location and country.

Figure 5.4 shows the stages of a full CO_2 project from site selection through to injection operations and monitoring. The full life cycle of a project can be divided into three distinct stages that are defined by their process: site selection, operations and monitoring (see Box 5.2 for details on the CO_2 monitoring process).

Figure 5.4. An example CO_2 storage project life cycle. Three key stages are site selection, operations and monitoring. Each stage has a set of processes that enables project decisions to be made and in turn allow subsequent progress through the stage gate process of the life cycle.



Source: Halliburton

Box 5.2

Risk of CO_2 leakage

The primary concern with a CO_2 storage project is the risk leakage either during or after injection, hence the processes conducted during the design and implementation of a project aims to avoid any such leaks. Leakage, defined in ISO27914: 2017 is any migration out of the pre-determined storage complex. Any leakage that reaches the seabed or atmosphere is defined as emissions (ISO 2017). The main areas where CO_2 can leak from the storage reservoir are shown on the Figure 5.5.

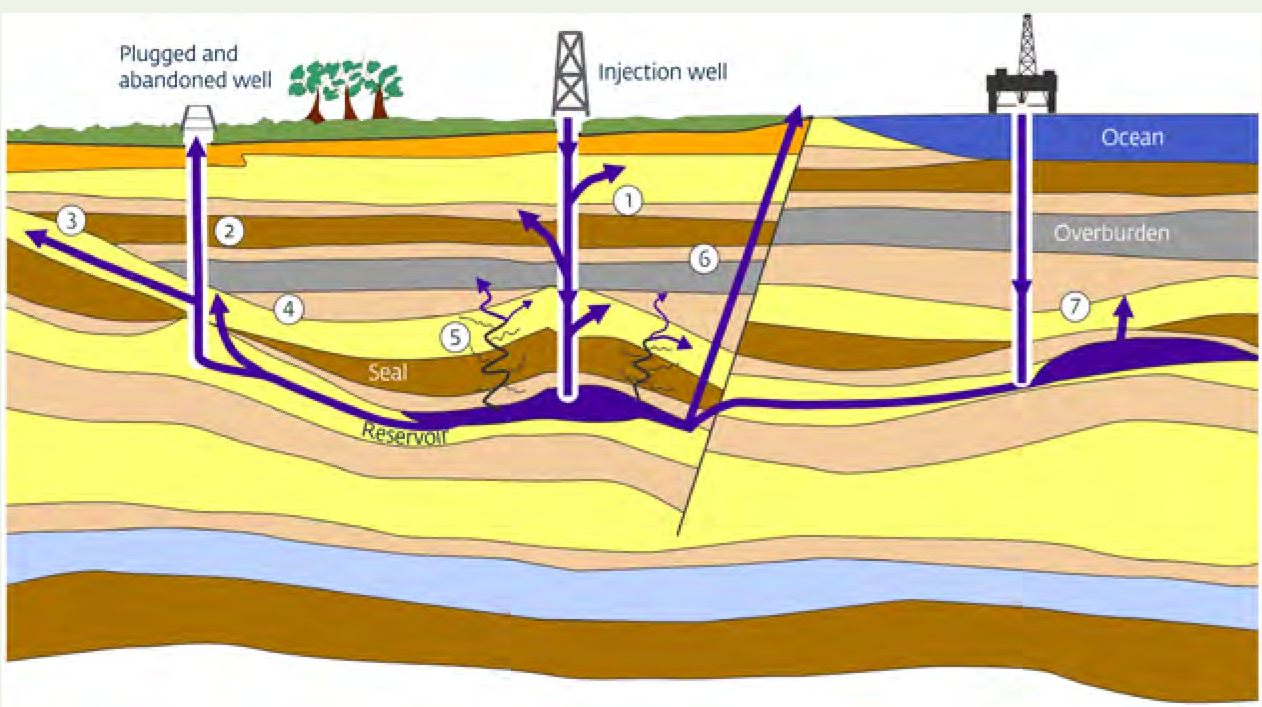
Well related leak pathways:

1. Seeps and leaks via the injection wellbore due to casing and cement failure from exposure to reservoir fluids.
2. CO_2 leaks and seeps through plugged and abandoned wells which do not have effective barriers throughout.

Geological related leak pathways:

3. CO_2 migrates up-dip of the reservoir and seeps to areas stratigraphically above it and potentially above the main caprock or containment unit.
4. Migration through gaps in sealing rock, rendering it ineffective as a barrier to CO_2 migration.
5. Over-pressurisation of the reservoir from injected CO_2 causes fractures and reactivation of faults that provide migration pathways for CO_2 to migrate out of the reservoir.
6. Seeps via non-sealing (transmissive) faults to other areas of the storage site.
7. The ultimate reservoir pressure (Pmax) and the Bottom Hole Pressure (BHP) exceed the safety margin of 80-90% below the fracture pressure of the caprock.

Figure 5.5. A schematic representation of the leak pathways from a CO_2 storage unit. Both onshore and offshore CO_2 storage injection sites are shown for illustrative purposes, but the same risk principles apply to both types of sites.



Source: Modified after IPCC 2005

Monitoring, Measuring and Verification (MMV)

The strategy of any MMV plan is to ensure safe and effective storage and must cover all phases of the CO_2 injection operation. The MMV plan should differentiate what is needed before, during and after injection. A full MMV plan shall incorporate all corrective measures that would be required in the unlikely but possible event of anything anomalous being detected by any of the monitoring techniques proposed. The conceptual MMV philosophy includes the procedural barriers and options to identify anomalies that would help decide on the adequate and proportionate corrective measures.

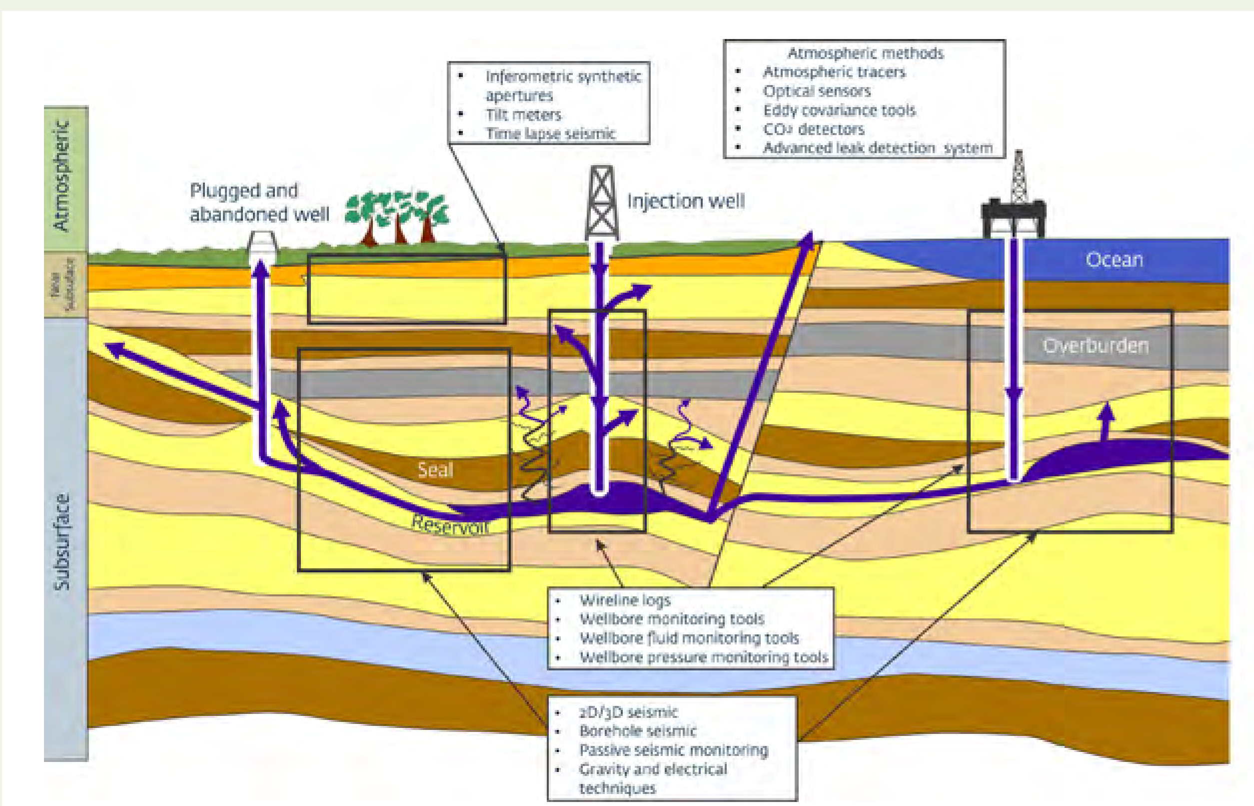
Among the most important objectives of any MMV plan, there are:

- Ensure containment: demonstrate effective and secure CO_2 storage.
- Ensure conformance: demonstrate that actual storage performance is consistent with prediction of injectivity, resources and CO_2 behavior within the storage complex.
- Provide safeguards and early warning that trigger timely corrective measures.
- Enable possible early handover of liabilities.

The types of monitoring tools and techniques will cover three areas (Figure 5.6):

1. Atmospheric monitoring tools aims to detect any leak of CO_2 into the atmosphere. They are placed close to the potential leak areas.
2. Near surface monitoring tools aim to detect any CO_2 that may be near the surface and potentially leak from faults and wellbores. The techniques employed here can be more cost effective than atmospheric and subsurface tools.
3. Subsurface tools are designed to track the CO_2 plume as it migrates in the formation, assess any changes in its behavior, track pressure changes in the reservoir and monitor changes in the well.

Figure 5.6. A schematic representation of potential MMV tools and techniques that may be employed in a storage project. Also shown in purple are potential leak pathways that are identified in Figure 5.5.



Source: Modified after IPCC 2005, Schütze et al. 2015 *© Halliburton 2024*

The main focus of this Atlas is to present the potential for CO_2 storage in Nigeria and hence, whilst each stage of the CO_2 project life cycle merits extensive best practice guidelines, these are beyond the scope of the report. The following provides a brief view on a best practice framework for storage site selection which aims to illustrate a high-level perspective on the core stages that are needed for any storage site selection.

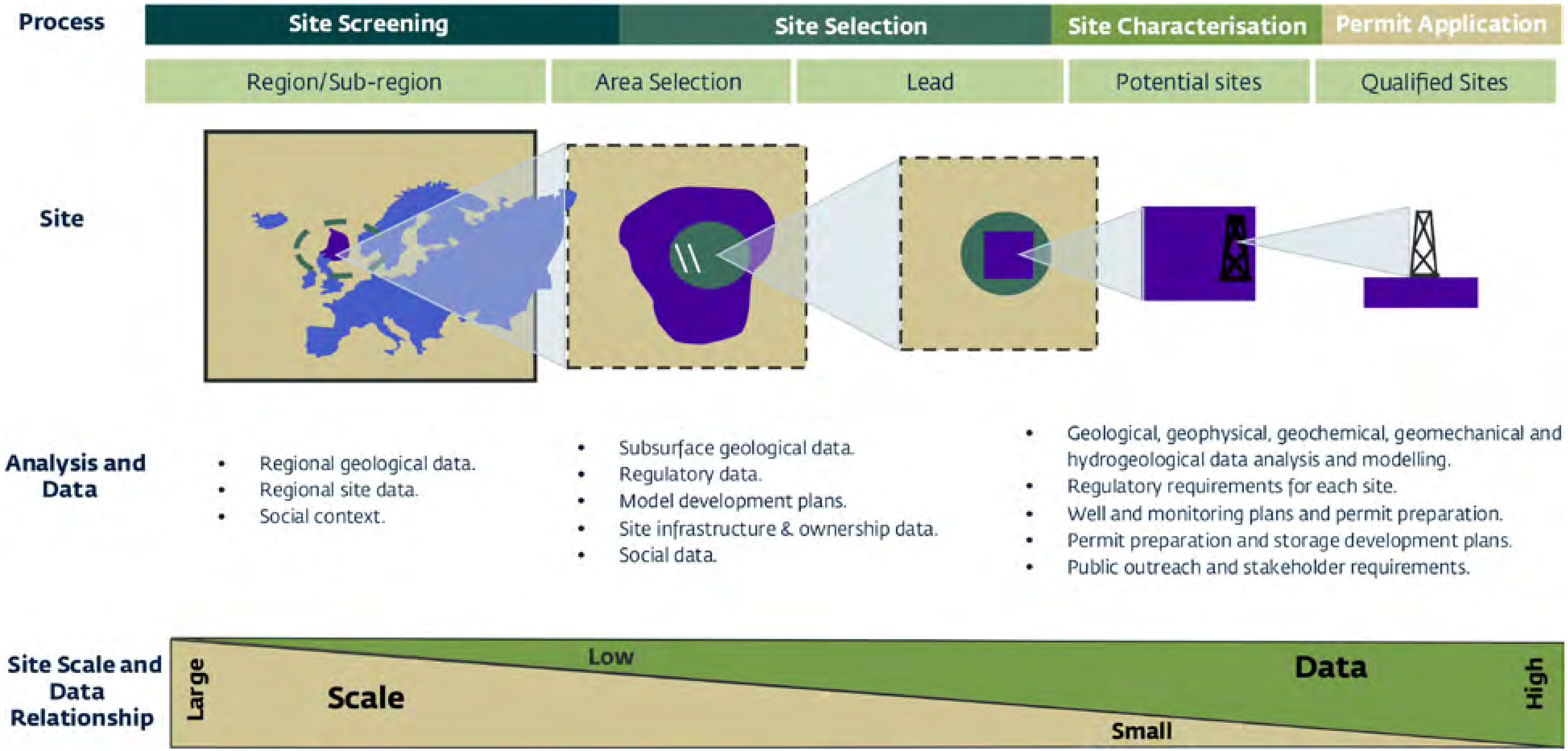
The process with which to develop a storage site operates on a number of scales and involves key processes from storage site screening, site selection, site characterization and site preparation for the development permit (NETL 2017) (Figure 5.7).

1. The first stage of site screening operates on a large scale (basin to sub-basin) and is usually based on relatively sparse data. Any analysis at this stage aims to high-grade areas for subsequent, more detailed characterization. The criteria for site screening selection will be defined in the project definition stage - this could involve a number of factors such as geological, social, environmental and economic considerations (NETL 2017). In terms of geological data analysis that needs to be done there four key steps: the first being the identification of the potential storage formations which includes understanding property characteristics such as porosity, permeability, formation thickness, salinity of the formation waters and pore pressure of the formation. Much of this data may be available from geological studies or potentially analogue data from adjacent or similar formations. The second and third type of analysis is to understand if the formations are at a suitable depth for injecting CO_2 and if there are confining zones that will be effective for limiting the vertical flow of CO_2 out of the formation (i.e. suitable trap and seal). The final analysis is to understand if the formations contain sufficient storage resources. In terms of cost, the majority of this data can be derived from publicly available research, geological surveys and other data sources such as oil and gas commissions. At this stage significant investment into data acquisition may not be needed. The outcome of this stage will be to define which potential storage resources may warrant financial investment for any potential data acquisition.

2. The next stage involves site selection and further evaluation in order to short list sites for characterization. Typically, data needed at this stage will be more extensive and site-specific. For example, geological data must be sufficient to provide an understanding of aspects such as formation properties, trapping targets, and injectivity potential. The subsurface analysis involved at this stage is to identify the storage reservoirs and the injection zones. This analysis can be performed by using available well and outcrop data. In addition, the confining zone where the CO_2 is to be injected, will need to be analyzed and understood more rigorously than the previous stage in terms of its aerial extent, thickness, porosity, permeability capillary pressure and any structural complexity. The target injection zones will also need to be understood from a geomechanical and injectivity perspective. Types of data needed to understand these aspects will be production history data, hydrological test data, core plugs and any well, outcrop and seismic data. This stage will need static and dynamic modeling to understand the potential behavior of the both the geology of the site from injected CO_2 and the potential migration of the CO_2. There may not be a wealth of data to perform these types of analysis so a key aspect it to define uncertainty parameters and boundary conditions – static and dynamic modeling can aid in defining these aspects. Understanding uncertainty will help frame what decisions need to be made in terms of new data acquisition. A cost versus benefit analysis will need to be done to determine the value of acquiring new data. This stage also requires the creation of a site development plan.

3. The site characterization stage will take successful storage site candidates from the selection phase into characterization stage. This stage aims to qualify the site suitable for CO_2 storage against all defined outcomes in the project definition. This stage will require in-depth analysis of regulatory, social and site suitability. From a geological perspective this stage demands extensive static and dynamic modeling of the reservoir and fluid injection, geomechanical analysis, testing of boundary conditions and multiple scenario modeling. The characterization phase will also necessitate injection and monitoring plans and a detailed development plan. This stage is also critical to deciding which data will need to be acquired. The data acquisition at this stage can be costly but necessary in order to perform proper site characterization. Surface data acquisition from outcrops, and mapping can provide some data for analysis of the storage reservoir and seal properties, but subsurface data will be needed for more effective understanding and risk analysis of the site

Figure 5.7. An example of the CO_2 storage site selection process. There are several processes from site screening to permit application that operate on different scales depending on the data availability and size of the area. Each process and subsequent process demands increasing data resolution and modeling to enable decisions through to the final site selection for permit application.



Source: Modified from NETL 2017

structure and properties. Subsurface data acquisition will involve conducting 2D or 3D seismic or other geophysical surveys to understand structural and stratigraphic organization of the storage site. Appraisal wells will need to be drilled for acquisition of key log data to understand the reservoir properties of the formation and the caprock integrity (NETL 2017). Seismic data acquisition and drilling appraisal wells is costly. A typical appraisal can cost 10s of millions of dollars (United States $ (USD)) to drill (with offshore wells being the more expensive to drill compared to onshore wells) (Ganat 2020). The acquisition costs of seismic data can depend on many factors (e.g. area of site, 2D or 3D seismic, type of seismic source, country logistics, labour costs and processing). This can run from a few hundred thousand dollars to several hundred million dollars (USD).

5.3 Storage Resource Management System

The Storage Resource Management System (SRMS) is an international system that classifies CO_2 storage sites in order to provide a consistent approach to defining sites in terms of development status for CO_2 storage. This also provides a framework where storage sites can be directly compared from one basin or country to another. The system is similar in design to the Petroleum Resource Management System (PRMS) used by the petroleum industry.

The SRMS aims to:

- Enable nations to map the progression of storage resource maturity.
- Create consistency in the use of resource terminology.
- Improve confidence regarding resource assessments with potential customers of CCS who are unfamiliar with subsurface issues (OGCI, 2022).

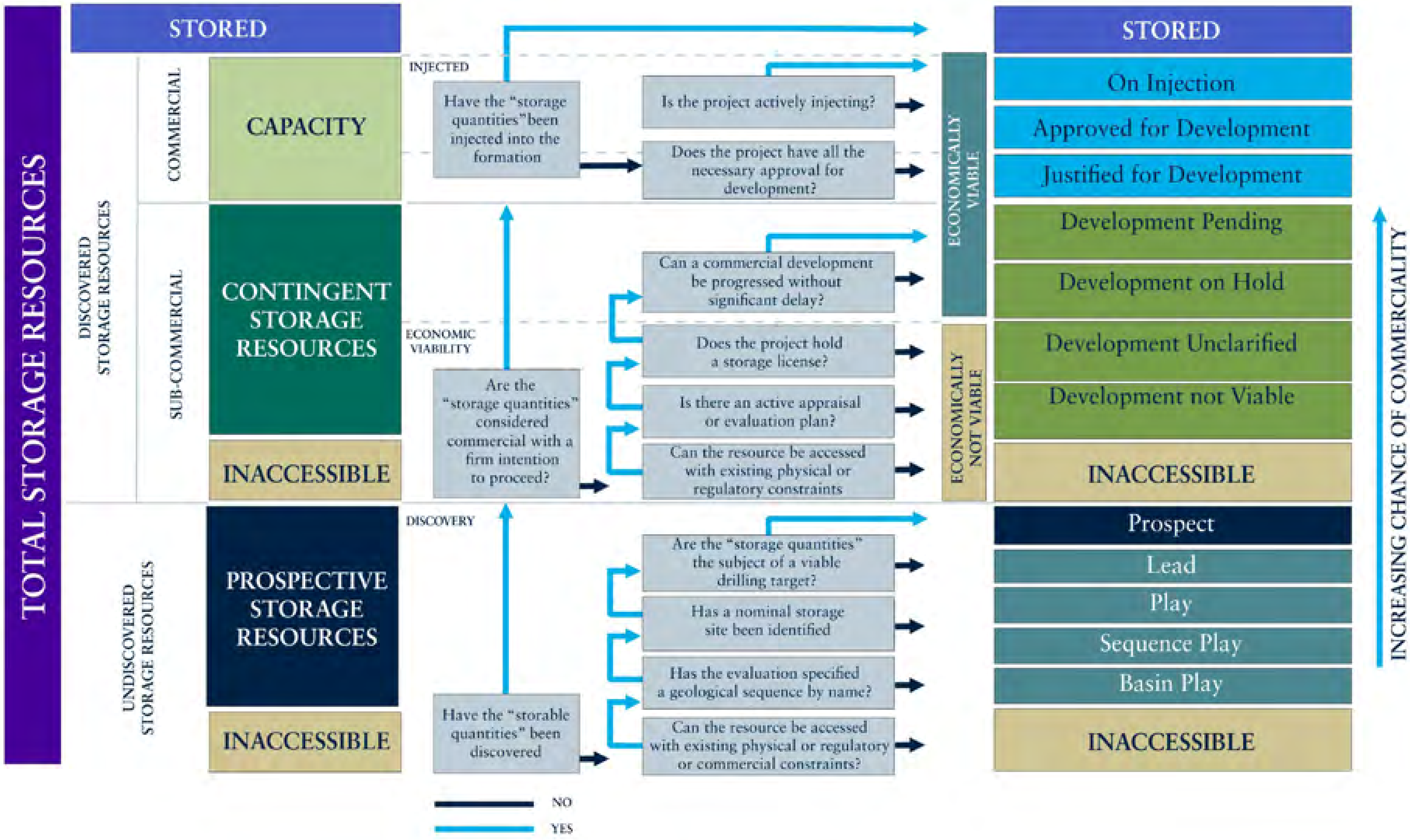
All SRMS guidelines and full details are published by the SPE (Society of Petroleum Engineers, 2017, CO_2 Storage Resources Management System). Nigeria's CO_2 storage resources (section 6.4-6.8) are classified according the SRMS.

5.3.1 Classification System

Storage sites are classified according to the SRMS flow chart shown in figure 5.8. Sites can progress along the flowchart and increase their maturity with respect to the SRMS classification mainly through commercialization steps.

The lowest classification between sites is that of discovery status. A 'Discovered' status is assigned when there is evidence of the formation having potential for CO_2 storage through drilling or sampling. Undiscovered sites are classified according to their evaluation status into either basin, sequence, lead or prospect. Discovered sites are defined through their commercialization status, which is attained by the level of appraisal, licensing or commercialization. A site may be classified as inaccessible if regulatory or physical constraints prevent access to the site's development. Many sites in Nigeria could theoretically be classified as Inaccessible due to the current absence of CCS regulations. However, since Nigeria is seeking to investigate the deployment of CCS as a component of it's net-zero pathway, then the SRMS classification of Inaccessible may be obsolete in the near future. Hence, all sites in Nigeria in this Atlas are placed in the Accessible category.

Figure 5.8. Flowchart for the classification of storage resources based on the SRMS guidelines and terminology.



Source: GCCSI 2020. © GCCSI

5.4 CO_2 Storage Resource Estimations

CO_2 storage resource estimations are a critical component of the storage site assessment to ensure that the site will be viable for the desired CO_2 injection volumes. Estimates can be performed on a variety of scales ranging from regional to basin to storage site. The type of storage site will also influence how meaningful resource estimations are. Estimations for saline aquifers can be complicated due the sparseness of data in these basins (Bachu, 2007a). Box 5.3 shows the methodologies that can be used to calculate storage resources.

Box 5.3

CO_2 Storage Resource Estimation Methodology

Confident estimations of CO_2 storage resources and scalability are key inputs to define marketable volumes required to build commercial agreements. There are different types of resource estimates that can be achieved depending on the data available for a given assessment. These are summarized by the techno-economic resource-reserve pyramid (Bachu et al. 2007a). The terms proposed include:

- Theoretical capacity – The physical storage limit.
- Effective capacity – An estimate using cut-off criteria.
- Practical capacity – Considering economic, technical, and regulatory factors.
- Matched capacity – Site specific storage.

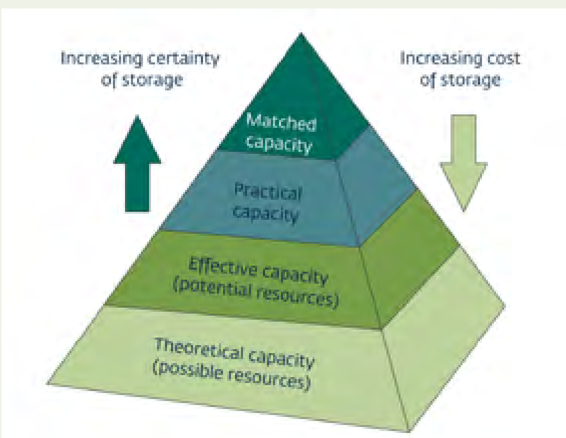


Figure 5.9. CO_2 techno-economic resource-reserve pyramid.

Source: Modified from Bachu et al. 2007

The resource pyramid is dynamic, whereby as projects mature with increasing cost, there is an increasing confidence in the storage potential. At the initial screening level, data availability, time and cost constraints mean that storage fairways can be compared via effective capacity and be high-graded rapidly and at a low cost.

Theoretical estimates are time-static, and determined by volumetric and compressibility variables that use basic rock and fluid properties. Dynamic calculations consider how the resource can change over time based on migration and trapping mechanisms (Ajayi et al. 2019). Several approaches have been employed to standardize theoretical calculation estimates. This can be challenging for comparing CO_2 storage sites. Therefore, to enable comparison of storage efficiencies and resources across basins, the most widely adopted are those established by the US Department of Energy (DOE 2007) and the Carbon Dioxide Sequestration Leadership Forum (CSLF) (Bachu et al. 2007b). Dynamic calculations are performed on a variety of numerical and analytical simulators designed to address specific modeling challenges with CO_2 injection. Resource estimates using dynamic simulations will be based on plume migration and trapping, fluid dynamics in the reservoir, geomechanical and geochemical reactions and pressure limitations.

5.5 Methodology Adopted to Create this Atlas

5.5.1 Current Status of CO_2 Storage in Nigeria

At present, few studies are available for CO_2 storage in Nigeria, with most of these being limited to the Niger Delta area (Umar et al. 2020 and Yahaya-Shiru et al. 2022). Furthermore, the majority of Nigeria's geological data is restricted to the Niger Delta region primarily due to the active hydrocarbon industry that operates there. Due to knowledge gained from the hydrocarbon industry, this area has the potential for CO_2 storage in depleted oil and gas fields and saline aquifers. There are a total of 606 fields in the Niger Delta area; only 193 of these are currently producing and 23 are non-operational (either abandoned or shut down). This potential in depleted oil and gas fields has been estimated to have a storage capacity of between 675-900 Gt (Ugwuishiwu et al. 2019).

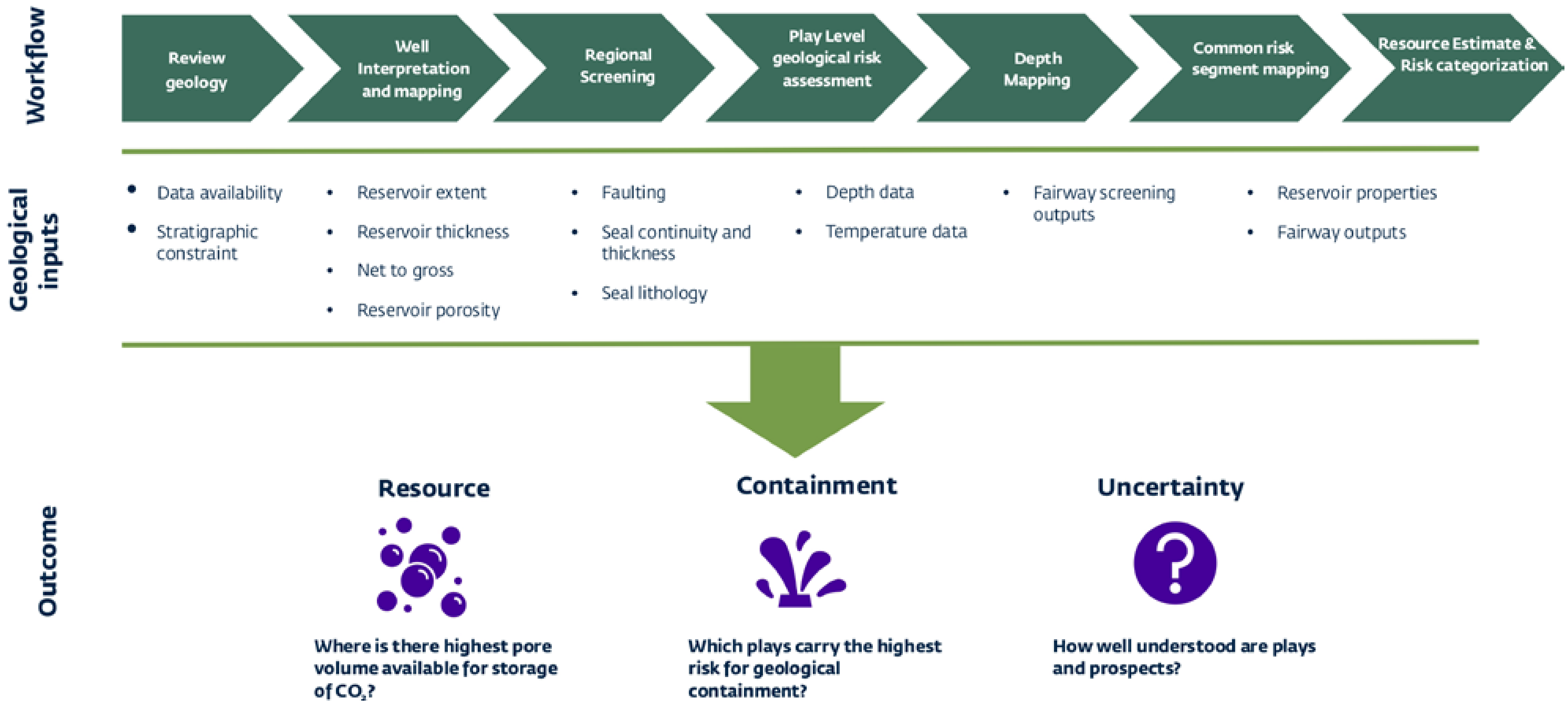
In addition to some promising CO_2 storage sites in the Niger Delta region, the country has several other basins that could present viable opportunities, although there is limited understanding of these due to sparsity of subsurface data, such as wells and seismic. Therefore, to assess Nigeria's countrywide CO_2 storage a different approach from classic subsurface studies is needed. This Atlas presents the opportunities for CO_2 storage by leveraging a play-based, regional screening approach and represents a unique first-of-its-kind study within the country allowing unbiased comparison across all regions. Several workflows built from geological datasets have been applied to assess the CO_2 storage potential in Nigeria. The dataset, its principles of origin, data limitations and the detailed workflows used are referenced in Appendix 2.

5.5.2 Overview of CO_2 Storage Site Identification Methodology

The broad workflow followed is indicated in Figure 5.10. The following steps have been used to assess the distribution of potential storage sites:

1. Review of regional geology and data availability.
2. Interpretation of data into a stratigraphic framework to build sequence stratigraphic interpretation for gross depositional environment maps.
3. Regional screening of Nigeria for areas where suitable depth and temperature exist for CO_2 storage and also areas that have an absence of tectonic activity.
4. Play-level review of basin geology, data availability and reservoir-seal pair identification for CO_2 storage.
5. Basin depth mapping.
6. Combined Common Risk Segment mapping (CCRS).
7. Resource estimates, risk categorization and SRMS Storage Resource Management benchmark.

Figure 5.10. Broad overview of workflow used to assess the CO_2 storage potential of Nigeria. Included also are the geological data inputs. The overall aim of the workflow is to gain an insight into the resource, containment and uncertainty of the storage plays in Nigeria.



Source: Halliburton

The studies used to compile the Atlas will show the potential of Nigeria's CO_2 storage opportunities by:

1. Assessing the sites within the context of their geological viability, based on the existence of key geological parameters for CO_2 storage. These are: the presence of a suitable reservoir at the correct depth and temperature for supercritical CO_2, the presence of a suitable seal for the reservoir, and an absence of active tectonic processes. Site assessments are presented by geological Period or Epoch depending on data (e.g. Cretaceous, Paleocene, Eocene).

2. A geo-risk assessment for each site. The sites are ranked according to geological risk of CO_2 containment. An uncertainty parameter is also applied to this assessment (see section 5.5.4).

3. A calculated volumetric storage resource estimate for each site (see section 5.5.3).

4. A classification of the sites according to the SRMS scheme (see section 5.3).

5.5.3 Storage Resource Estimates

For each of the high-graded areas from the CCRS workflow, a total prospective CO_2 storage resource estimate is made, allowing comparison between the different plays and basins. This is calculated following the methodology (Box 5.4) outlined by the U.S. Department of Energy's National Energy Technology Laboratory (U.S. DOE NETL 2015), with an adjustment for net, rather than gross rock volumes. This prospective CO_2 storage resource estimate is based on how much the accessible, high-graded area could hold if it was filled with CO_2 at an expected sweep efficiency for the reservoir lithology type. This is therefore much higher than a prospect-by-prospect-based storage resource estimate, where the total storage resource is calculated by summing the storage resource estimates of each potential storage site. The selection of the storage efficiency factor (equivalent to sweep efficiency of the injected CO_2) significantly impacts the estimated storage resource. This approach provides a useful and consistent methodology for comparison between basins where prospect identification is not possible (e.g. through lack of accurate subsurface data).

Box 5.4

Storage Resource Calculation

$$GCO_2 = A \times hg \times ftot \times p \times NG \times Esaline$$

Where:

- GCO_2 = Mass CO_2 that could be stored
- A = Total area. Calculated from the high-graded fairway areas
- hg = Gross formation thickness. Based on available literature data
- ftot = Total porosity. Based on averages from literature data
- p= CO_2 density at depth. Based on published estimates (Van der Straaten et al. 1996)
- NG = Net-to-Gross ratio. Based on averages from literature data
- Esaline = CO_2 storage efficiency factor. Derived from, 0.5% for low case, 2.0% for medium case and 5.4% high case (Goodman et al. 2011)

5.5.4 Geo-risk Methodology

A risk categorization was applied at a basin scale for geological risk of economic CO_2 containment ("geo-risk"). The risk assessment is based on several factors using categories based on published guidelines and best practice (IEA 2009 and CO_2Stored) (Table 5.1). A qualitative approach is used to allow for assessment across basins with differing data availability. For each assessed category, the number of published literature documents is used to support the assignation of geo-risk and hence used as a proxy to categorize the uncertainty in the result. For example, one high quality document may add more value than several poorer quality ones; however, this proxy gives an overall measure of the amount of attention given to a play for comparative purposes.

This assessment did not address factors of engineered risk, such as well density, which will be more relevant at the prospect scale. The risks assessed are shown in Table 5.1.

Once completed, the categorizations were transformed to a numerical value to allow for further data visualization using the following values: high risk = 6, medium risk = 3, low risk = 1. These are then formed into a uncertainty matrix with the proxy (amount of literature) as shown in Figure 5.11. The outcome of each risk assessment is detailed under each play assessment (sections 6.4-6.8) and presented in figure 6.3.

Figure 5.11. An uncertainty matrix used to provide a risk value for each assessed basin in Nigeria. The higher the number the greater the uncertainty and hence the greater risk.

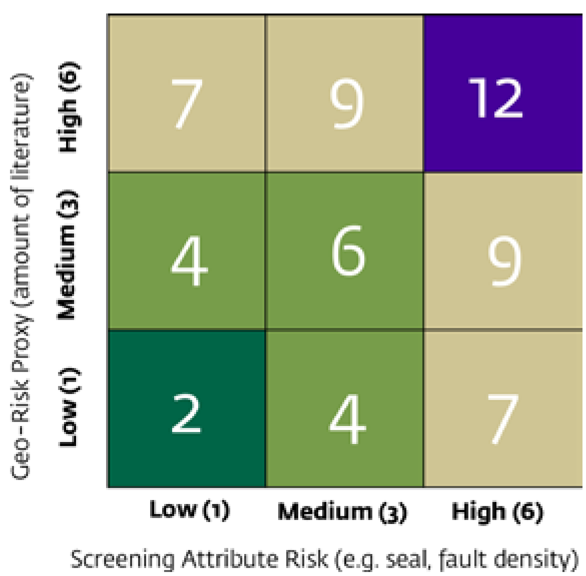


Table 5.1. The categorizations of risk used in this assessment. Categories based on CO_2 Stored 2023.

Geo-risk Category	Geo-risk Sub-Category	Low (1)	Medium (3)	High (6)
Seal	Seal Chemical Reactivity	Evaporites	Dominated by fine – very fine-grained silicate (mineralogically sub-mature – mature)	Seal includes carbonates, feldspar, ferromagnesian silicate and / or mineralogically immature
	Seal Degradation	No evidence of seal lateral pinch out, erosion, injection structures, leakage, base seal integrity if relevant (e.g. stratigraphic trapping component)	One of the following: seal lateral pinch out, erosion, base seal degraded if relevant i.e. with stratigraphic trapping component	One of the following: injection structures, evidence of overburden surface fluid/gas OR more than one of the following: seal lateral pinch out, erosion, base seal degraded if relevant i.e. with stratigraphic trapping component
Fault	Fault Density*	0-2 observed faults per unit	2-5 observed faults per unit	>5 observed faults per unit
	Throw and Fault Seal	None	Estimated offset less than caprock/inter-reservoir shale	Estimated offset greater than caprock thickness/potential from clay smear
	Fault Vertical Extent	Resolved fault displacement limited to reservoir and seal	Resolved fault terminates in overburden reservoir deeper than 800 m	Resolved fault displacement/conduit shallower than 800 m
Reservoir	Reservoir Thickness	>50 m	20-50 m	<20 m
	Reservoir Depth	In-between 800 m – 3000 m	greater than 3000 m	less than 800 m
	Reservoir Porosity	>20%	10-20%	<10%
	Reservoir Permeability	>300 mD	100-300 mD	<10-100 mD
	Reservoir Salinity	>300,000 mg/l (ppm)	100,000 - 300,000 mg/l (ppm)	<100,000 mg/l (ppm)
Stratigraphic		Formation extent and depth constrained by >30 wells or 3D seismic covering over 60% of the play or >5 interpreted 2D seismic and cross sections	Formation extent and depth constrained by 5-30 wells or 2-5 interpreted 2D seismic	Formation extent and depth constrained by <5 wells or 0-1 interpreted 2D seismic and cross sections
Geo-risk		Geo-risk assessment based on >=5 publications with data	Geo-risk assessment based on <5 publications with data	Geo-risk assessment based on literature with no data support

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6 CO_2 Storage Potential in Nigeria

6.1 Geology of Nigeria

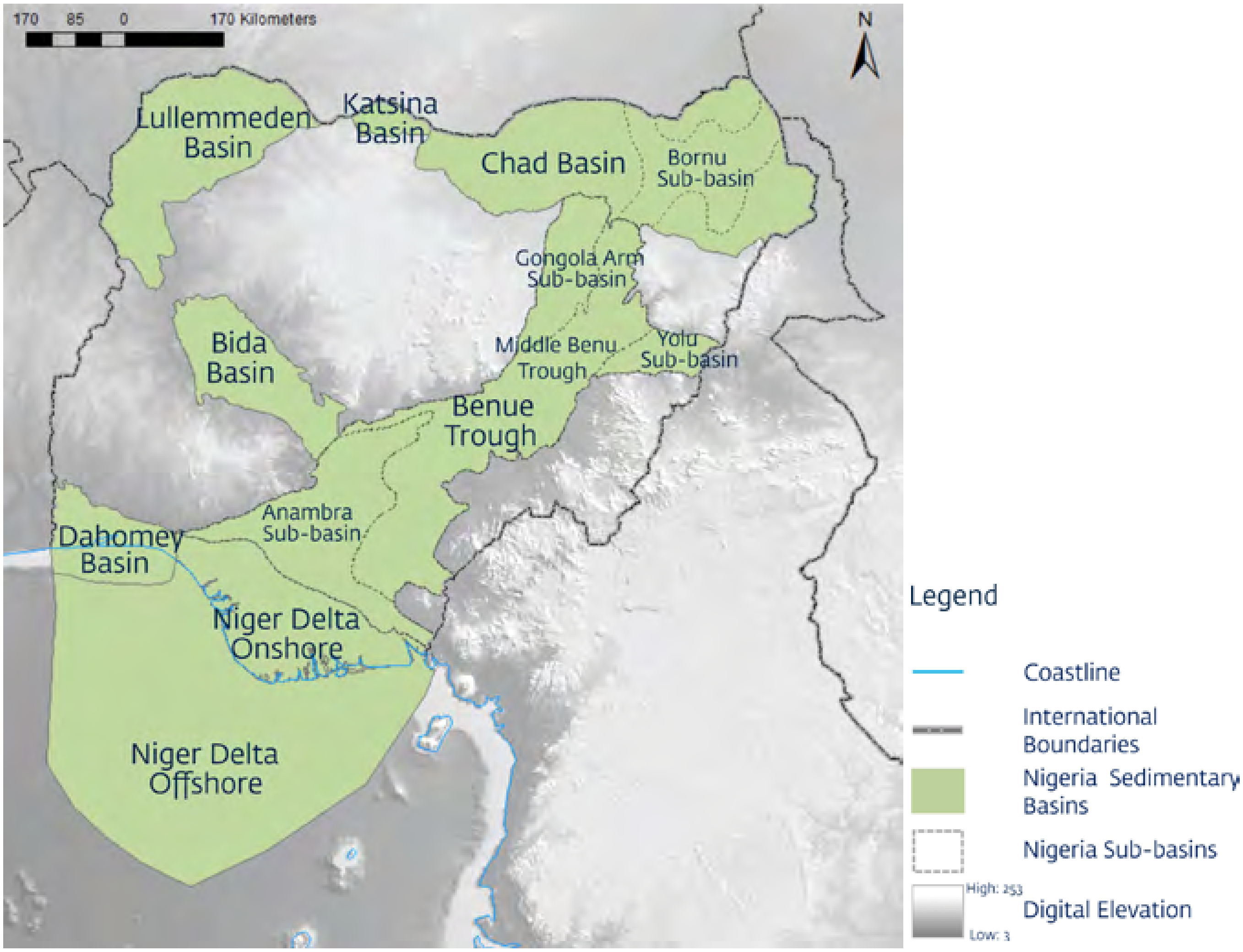
The sedimentary geology of Nigeria is split into several basins (Figure 6.1), which are depressions in the Earth's crust formed due to tectonic activities and passive and/or thermal subsidence. Sedimentary material accumulates in these basins over time and is subsequently compacted and buried as accumulation continues. Each of these basins have their own unique geological history that impacts the potential for CO_2 storage. In areas outside of these basins, there exists only crystalline basement outcrops with no sedimentary rock in-fill, meaning that potential conventional target reservoirs for CO_2 storage are absent.

Nigeria's geological history extends back to the Neoproterozoic (see Appendix 3 for details on geological time scale) where a series of orogenic events that spanned ~650-515 Ma (Begg et al. 2009, Scotese et al. 1999), culminated in the formation of the supercontinent called Gondwana (incorporating present-day South America, Africa, Arabia, Madagascar, India, Australia, and Antarctica). Around the start of the Palaeozoic era (in the Permian period) Gondwana collided with present-day North America, Europe, and Siberia to form the supercontinent of Pangea.

The oldest known sedimentary rocks in Nigeria are sandstones and shales, penetrated by offshore wells in the Dahomey Basin, associated with the earliest stages of Pangea's breakup during the Barremian age (~130-125 Ma).

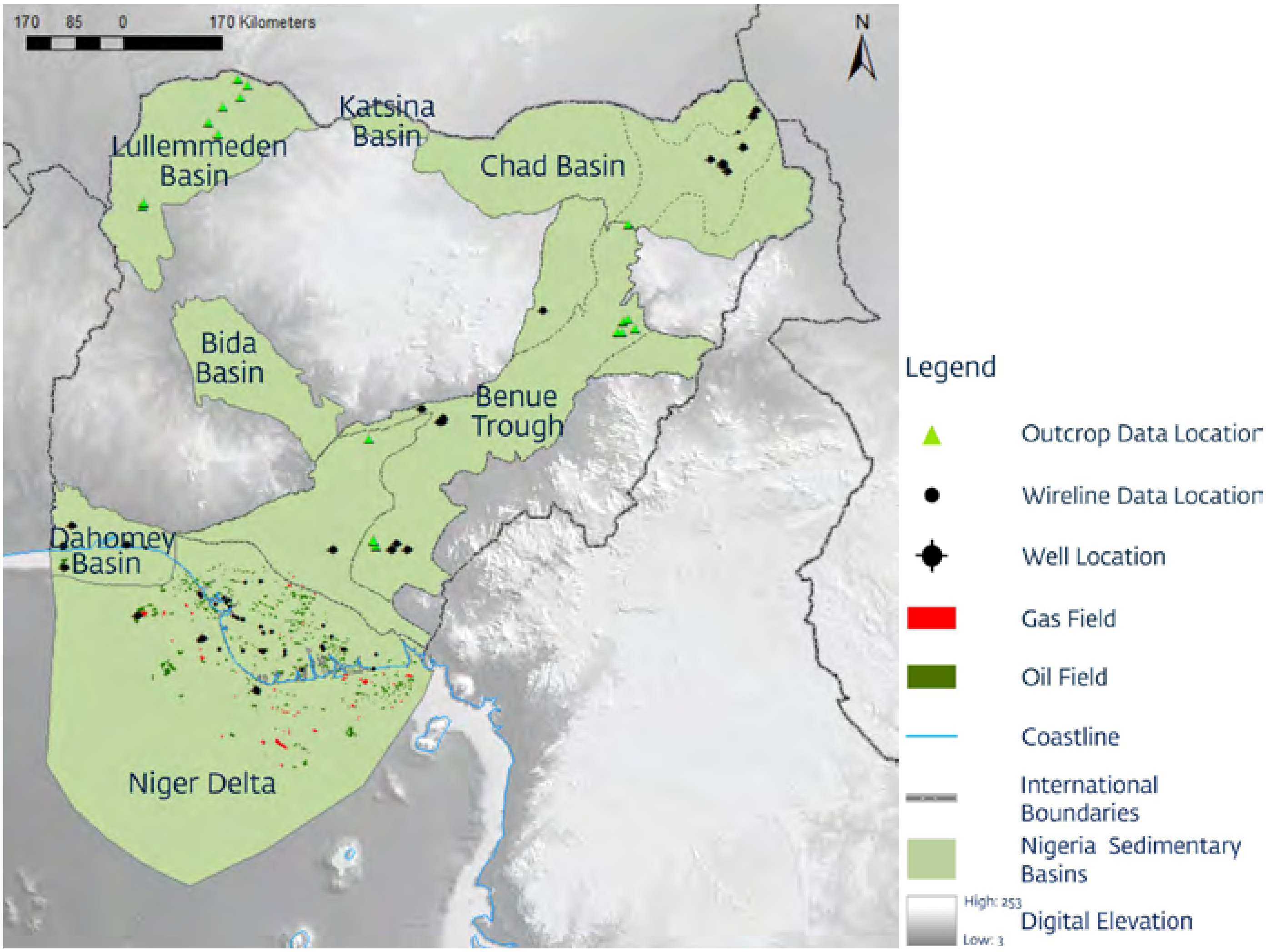
Continued separation between Africa and South America throughout the Albian age (Figure 6.2a) created major sedimentary basins along both the rift margin (present coastline), and the West and Central African Rift System, which includes the Chad and Benue basins, into which very thick sequences of continental sandstones and shales were deposited. During the Cenomanian and Turonian ages, rifting in the Benue Trough and oceanic spreading in the South Atlantic (Figure 6.2b) resulted in the formation of a seaway that ran the length of the Benue rift and through the Chad Basin, connecting the Tethys (now non-existent) and Atlantic oceans, resulting in deposition of widespread open-marine facies that often exhibit good seal characteristics (Figure 6.2d-e). Rifting ceased in the Late Cenomanian age. During the Santonian age (~85 Ma), a brief period of inversion, compression and folding occurred across the entire African plate, resulting in the development of a regional unconformity across Nigeria. It also created significant folding and faulting in earlier Cretaceous sediments in the Chad and Benue basins (Ahmed et al. 2022 and Obaje 2009). Gradual uplift of the South African plateau to the south and the Tanzanian Craton to the east throughout the Late Cretaceous age caused significant deposition of Cenozoic sediments in the Benue Trough and Anambra Sub-Basin (Figure 6.2f-g).
Growth and expansion of drainage networks throughout the Paleogene period brought increasing volumes of sediment into the Nigerian offshore, resulting in the development of the major Niger Delta system along the South Atlantic margin, which continues to this day (Figure 6.2f-g). Maximum subsidence and sedimentation occurred in the Neogene period with over 10 km (thickness) of sediments deposited. During this time, a combined proximal extensional and distal compressional system within the Niger Delta led to an extensive fault and fold system.

Figure 6.1a. Map of sedimentary basins of Nigeria. Outside of these it is assumed that there is no CO_2 storage potential that meet the screening criteria for depleted oil and gas fields or saline aquifers.



Source: Halliburton

Figure 6.1b. Map of Nigeria sedimentary basins with oil and gas field locations. Also shown are locations of publicly available well and outcrop data that are used in this study. A full review of data used in compiling this Atlas is provided in Appendix 2.



Source: Halliburton

Figure 6.2a. Paleogeographic reconstructions of Nigeria in the Albian

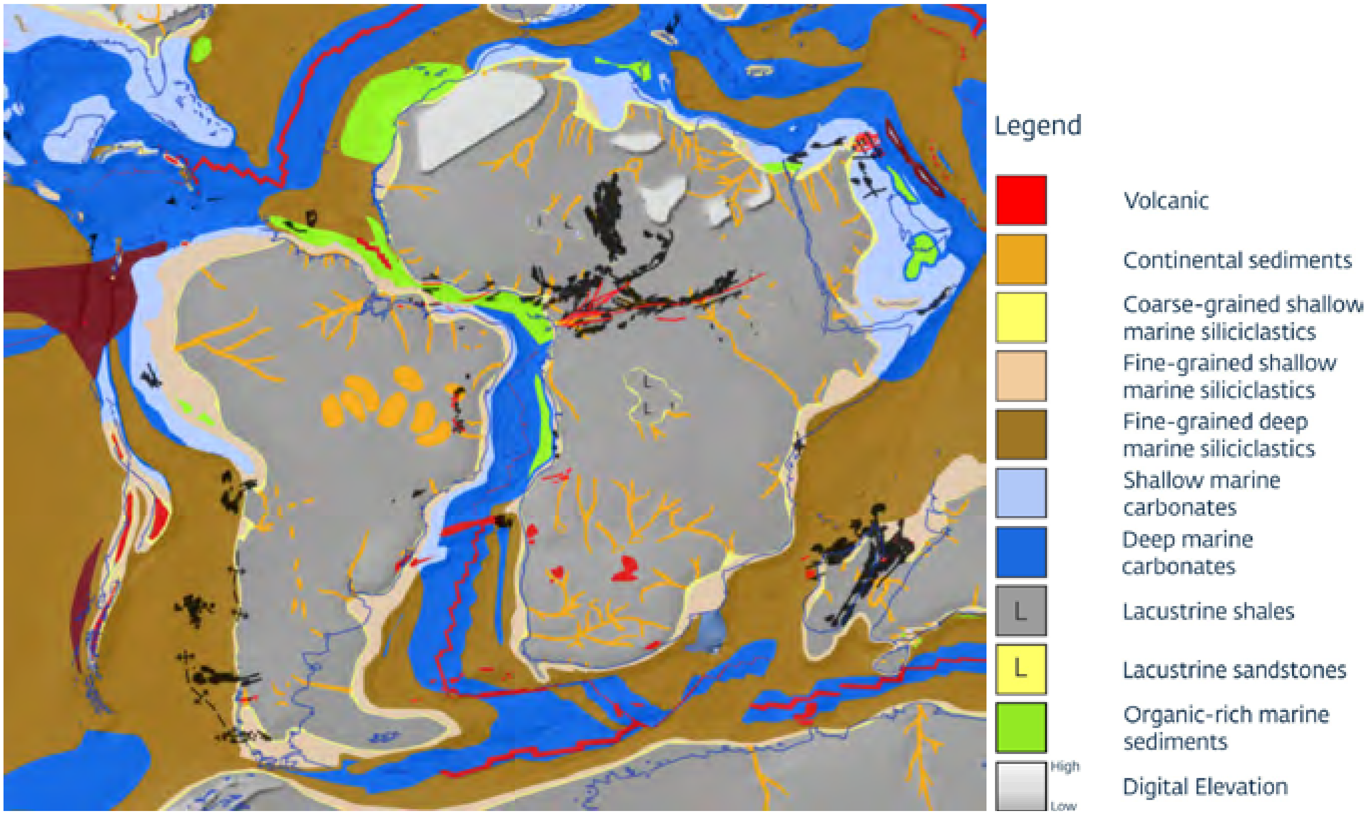


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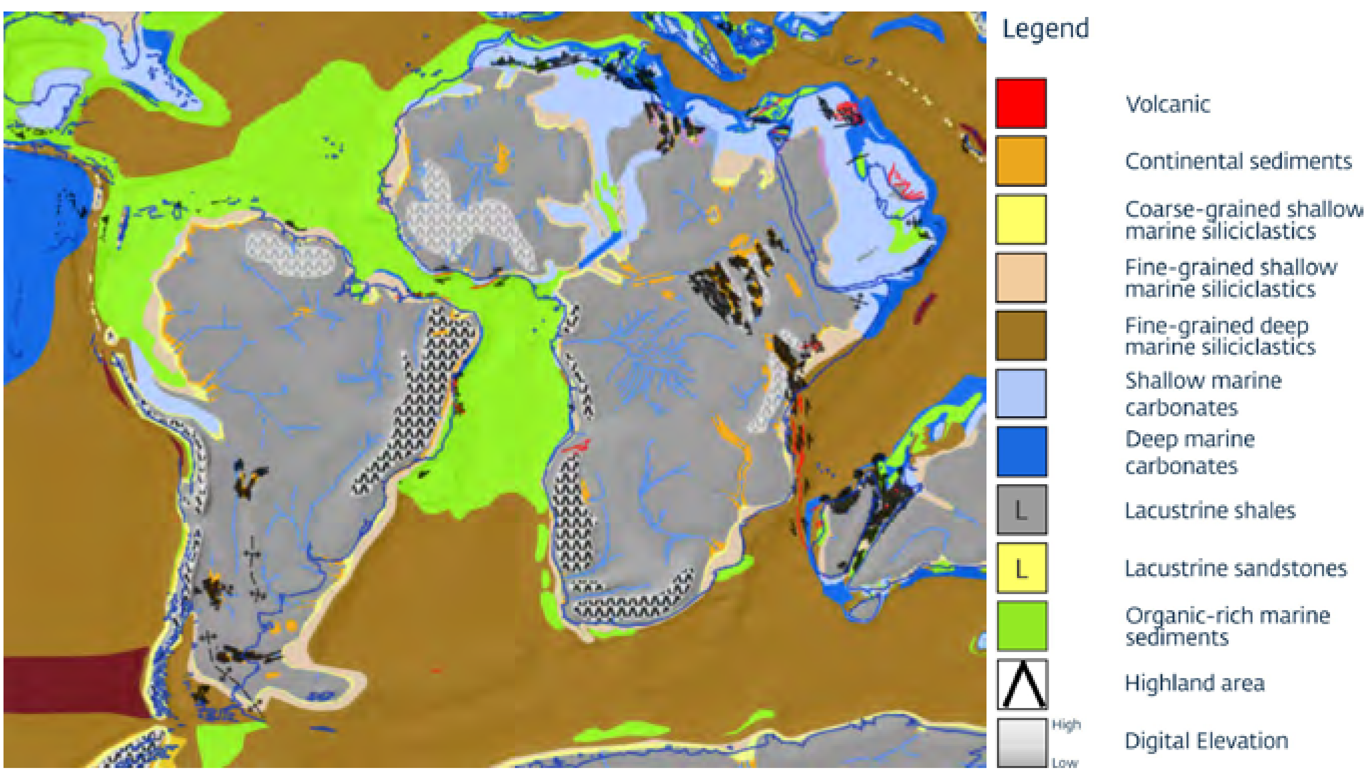
Figure 6.2b. Paleogeographic reconstructions of Nigeria in the Cenomanian



Source: Halliburton

Figure 6.2c. Regional gross depositional environment map of Nigeria showing the major sedimentary systems and depositional history of Nigeria's sedimentary basins in the Albian-Cenomanian.

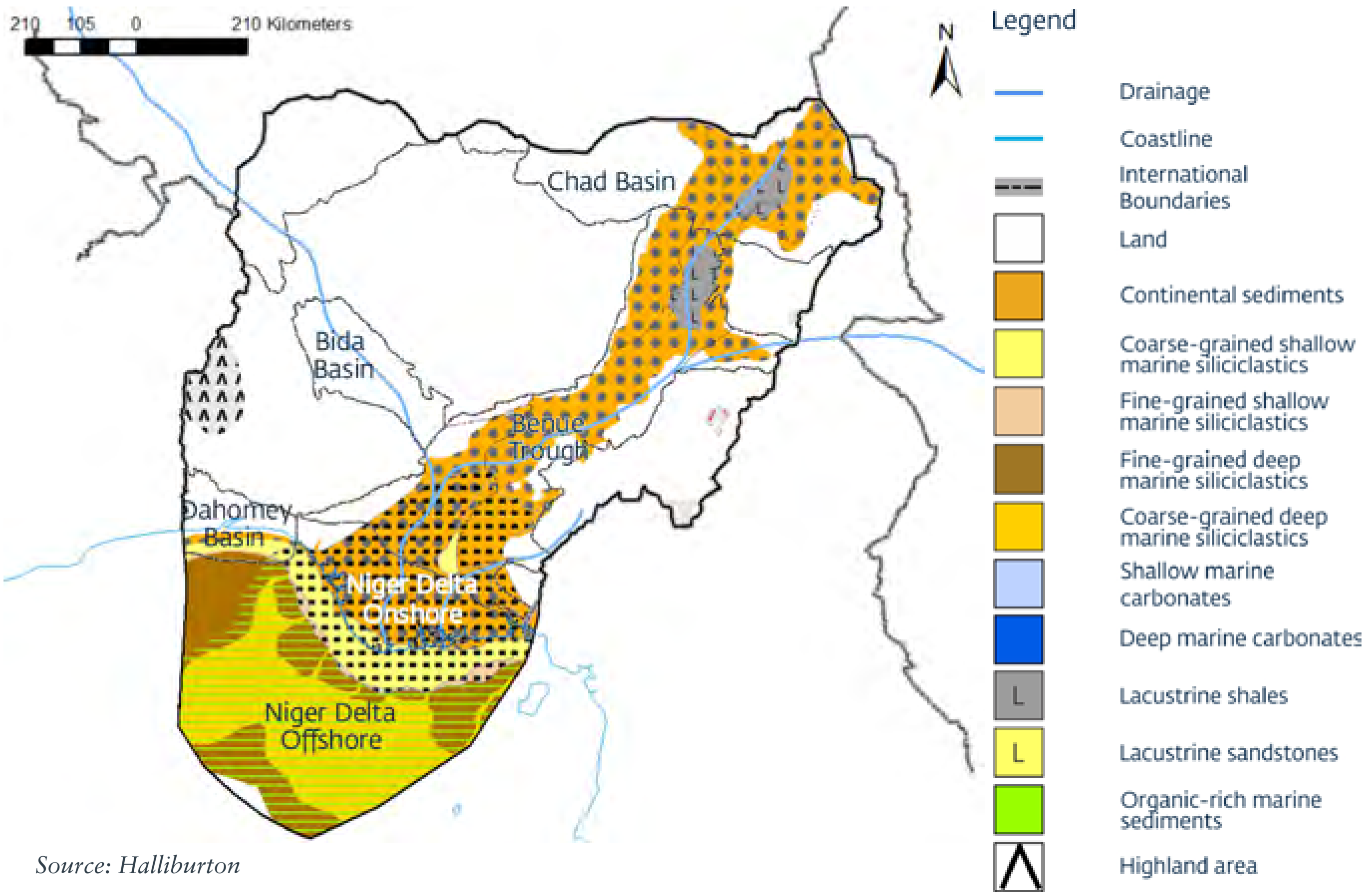


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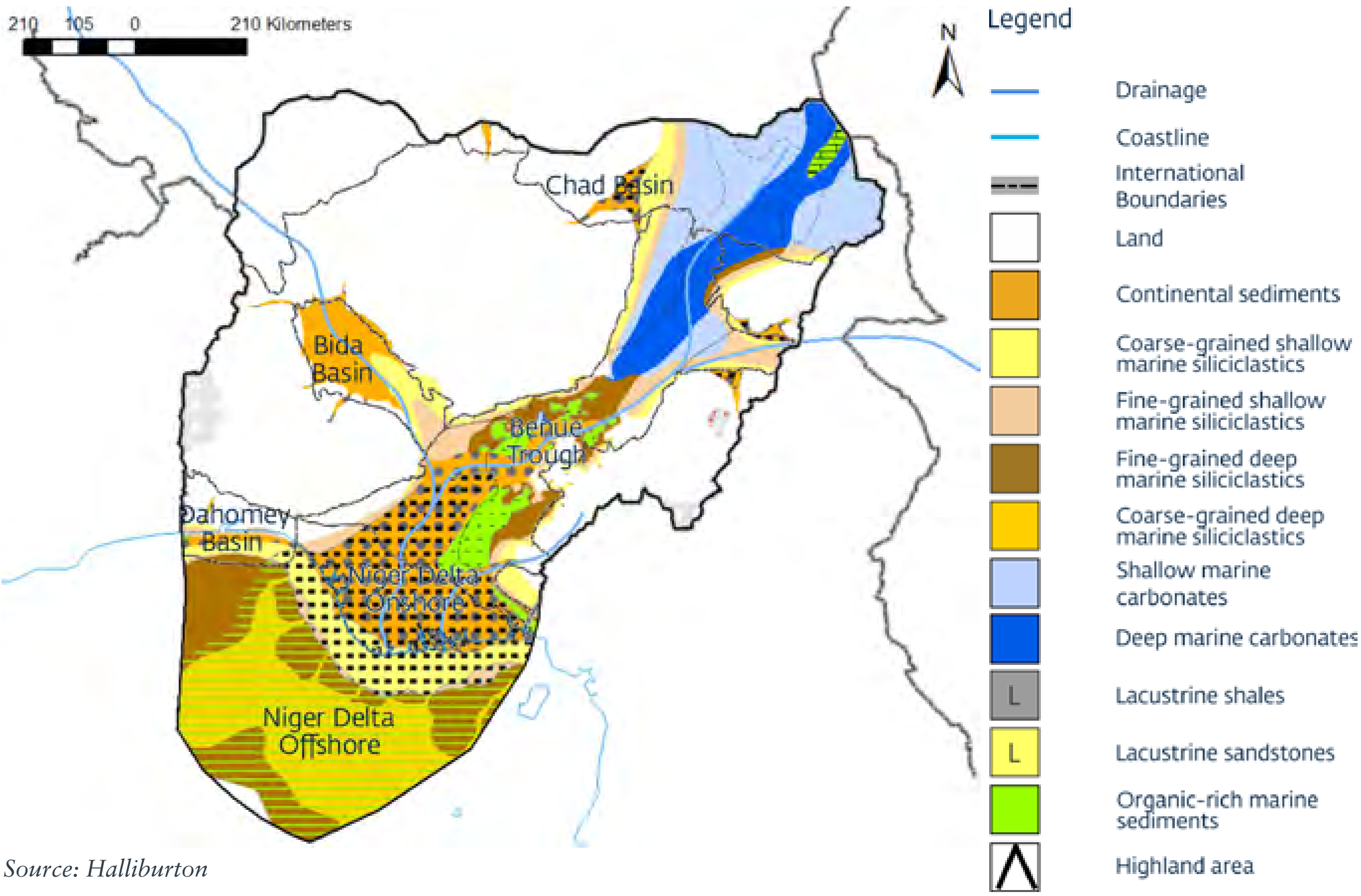
Figure 6.2d. Regional gross depositional environment map of Nigeria showing the major sedimentary systems and depositional history of Nigeria's sedimentary basins in the Turonian-Coniacian.



Source: Halliburton

Figure 6.2e. Regional gross depositional environment map of Nigeria showing the major sedimentary systems and depositional history of Nigeria's sedimentary basins in the Santonian.

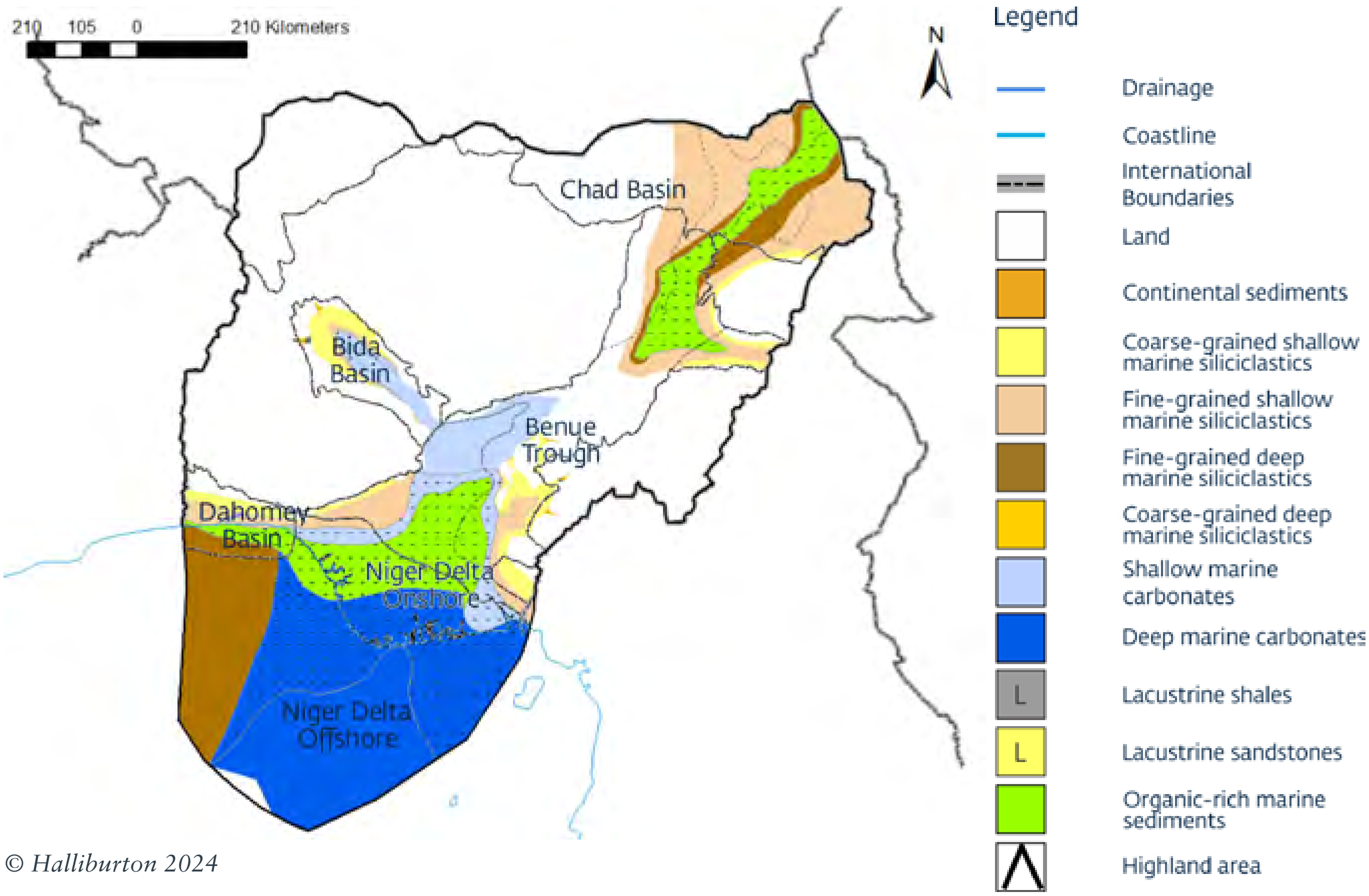


Figure 6.2f. Regional gross depositional environment map of Nigeria showing the major sedimentary systems and depositional history of Nigeria's sedimentary basins in the early Paleocene.

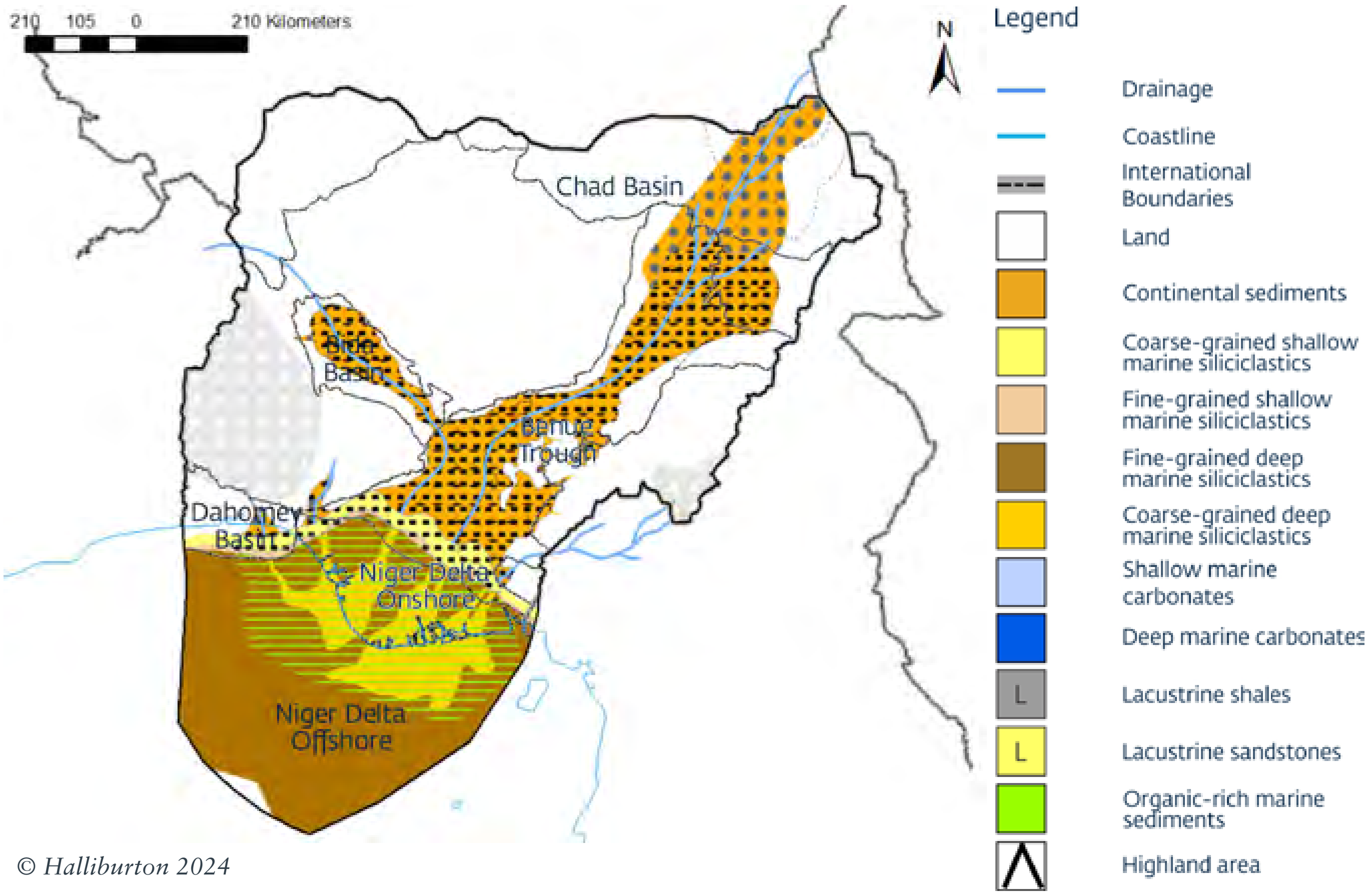
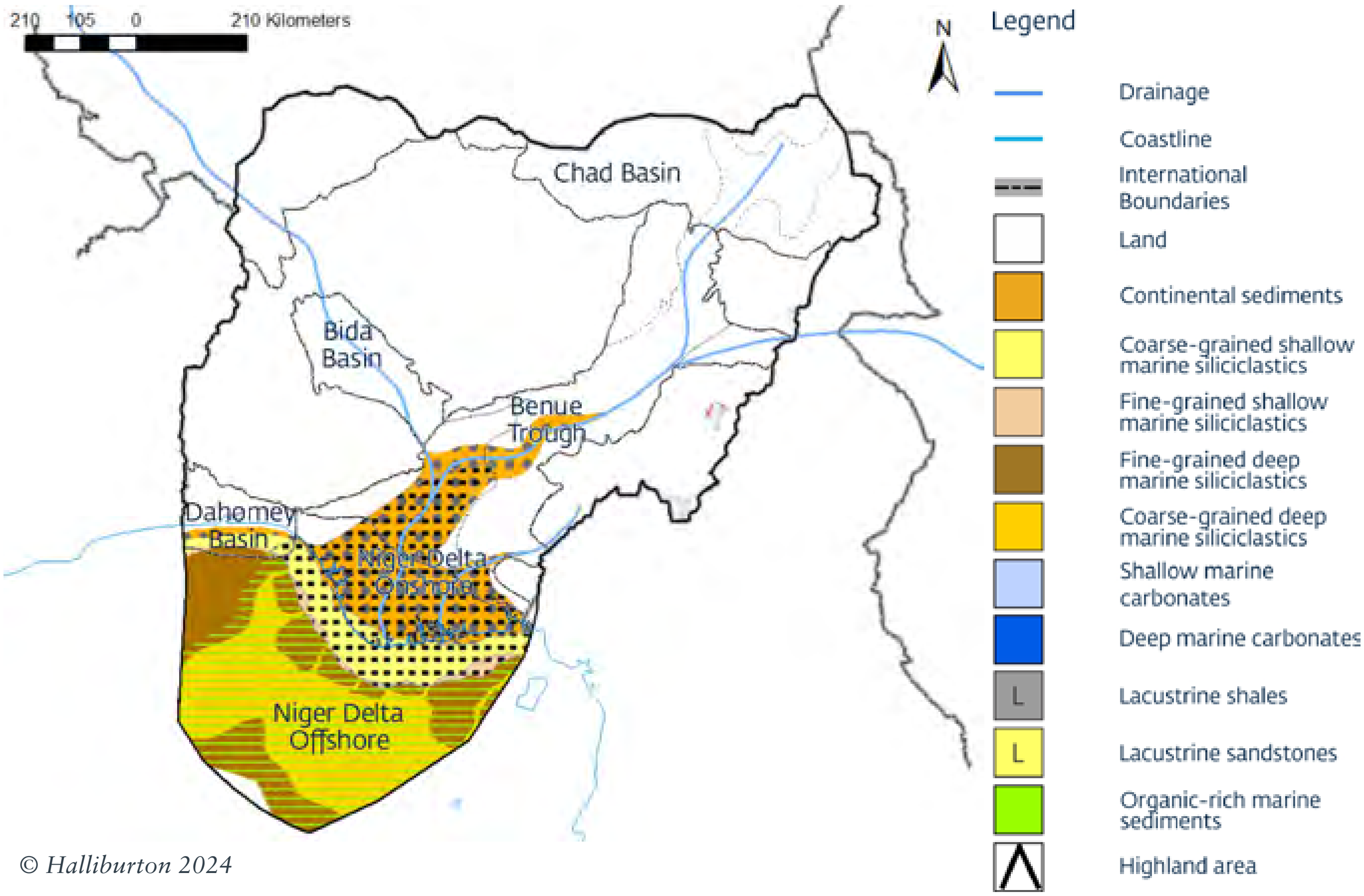


Figure 6.2g. Regional gross depositional environment map of Nigeria showing the major sedimentary systems and depositional history of Nigeria's sedimentary basins in the late Miocene.



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6.2 Summary of Nigeria CO_2 Storage Plays

Niger Delta

In the Niger Delta, proven extensive hydrocarbon plays demonstrate the reservoir, sealing and trapping potential of the stratigraphy for CO_2 storage. Due to the well-defined mega sequences within the delta, multiple horizons have been mapped within the play to capture the extent of the fairways more accurately. Fault compartmentalization and active fault stress regimes are a known risk within the basin and should be taken into consideration for CO_2 storage. In addition, there are many sources of CO_2 located in this area which reduces transportation challenges. The abundance of oil and gas fields provides a portfolio of potential storage sites; however, further structural and pressure mapping to define aquifer prospects would be beneficial. Based on the CCRS mapping (Figures 6.9c, 6.10c, 6.11c) and the estimated gross storage capacity of each play (Table 6.2), the Miocene plays are the most favorable for CO_2 storage.

Dahomey Basin

The Dahomey Basin is a known hydrocarbon province with working petroleum plays, meaning that there are proven reservoir – seal pairs for containing liquids and gases long term. However, the basin and overall fairway areas are both limited, leading to a small prospective storage resource. Overburden depth quickly builds towards the offshore, meaning the most accessible storage is onshore, away from the known hydrocarbon fields, and thus aquifer storage is the preferred option in this basin. Further structural, lithological, and rock property and pressure data will be needed to delineate aquifer storage prospects in this area. The onshore area is also known for oil sands, which may indicate that traps are not fully sealed, creating a risk that will need to be further investigated. Overall, the potential storage resource of this basin is not considered to score as highly as neighboring basins.

Chad Basin

Based on the geological risk and formation characteristics, the Bima/ Gongila sandstones and overlying Gongila/ Fika shales represent a potential reservoir-seal pair for CO_2 storage in the Chad basin. The higher density faulting in the earlier stratigraphy will need significant studies to determine its effect on the integrity of any potential traps.

The Chad Formation, however, has a shallow depth and given its role as a major aquifer could present a significant safety risk for the contamination of drinking water systems and therefore unlikely to be a future storage target. The basin as a whole has vertical migration and leakage of hydrocarbons which is well documented and suggests that CO_2 containment could be a risk.

Due to limited well data (Figure 6.1b), there is a high degree of uncertainty on the distribution of these reservoir-seal pairs, so significant future data collection would be required to better predict the distribution and effectiveness of the individual play elements. It is also worth noting that there are no major CO_2 source locations proximal to this basin. Significant further research and data generation effort will be required to truly understand the prospectivity of these basins.

Benue Trough

The Benue Trough holds several potential storage systems, with a relatively high potential storage resource and an extensive fairway. However, the basin has very limited data coverage and further data gathering would be needed to define any aquifer prospects in this area. Although geo-risk was initially assessed as quite high, further data would likely alter this assessment. The proximity to CO_2 sources outside the Niger Delta area makes this area worthy of further consideration. Overall, there is low data coverage across most of the Benue Trough; however, some data are available to provide a high-level screening of the plays in this basin. The Maastrichtian formations are not considered to have good storage potential for CO_2 due to the lack of proven seals. Older formations have better storage potential; however, the oldest Albian – Cenomanian play in the Northern Benue Basin may be lacking an effective seal and may be reliant instead on the overlying Turonian transgressive shales.

Bida Basin

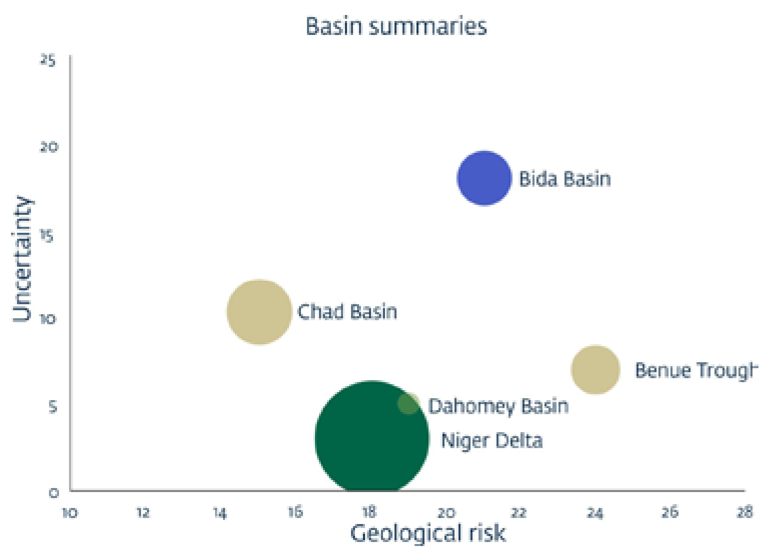
Only one potential storage play is identified in this basin and this is based on extremely limited data. Significant exploration and data generation activity would be needed to understand this area further. Little is known about the stratigraphy of the Bida Basin due to the lack of wells (Figure 6.1b) and other exploration activity in this area. A potential reservoir-seal pair for CO_2 storage is mapped to exist in the basin; however, extensive data collection would be needed to better understand this play before it could be de-risked and considered for storage. There are limited CO_2 sources proximal to the center of the basin (Figure 6.24d); these are dominated by industrial cement production.

6.2.1 Summary of Geo-risk

This report took a regional and consistent approach to evaluating the storage potential of Nigeria, allowing for the identification of prospective areas for further study. The Miocene formations of the Niger Delta have been identified as carrying the greatest potential for CO_2 storage. Storage sites within the Niger Delta may benefit from having several stacked storage horizons, increasing the potential storage capacity of any pilot studies. However, care must be taken to evaluate prospect structures and containment risks as many fields in the Niger Delta are known to be highly faulted.

Based on the overall basin geo-risk assessment (Figure 6.3), on average the combined plays of the Chad Basin have the lowest geological risk; however, data constraint is an issue due to the lack of publicly available subsurface information, so there is a high degree of uncertainty in this assessment which subsequently increases the risk. The next lowest risk are the combined plays within the Niger Delta Basin. These have a low data uncertainty, with good data coverage in both the onshore and offshore. The Dahomey Basin has a relatively low geo-risk and low data uncertainty, making this a favorable candidate for pilot selection. However, there may be a high risk to containment of fluids in the subsurface, this is, in part, borne out by the presence of tar sands in the onshore part of this basin, showing that traps have leaked hydrocarbons in the past. The Benue Trough has the next highest average geo-risk; however, data uncertainty in this basin is also high. Very little data exists for the Bida Basin. To date, no exploration wells (Figure 6.1b) have been drilled and only a small number of shallow boreholes exist along the basin margins, therefore data uncertainty is high.

Figure 6.3. Summary of geo-risk and uncertainty for the Nigerian CO_2 storage plays (See section 5.5.4 for explanation on geo-risk categorization).

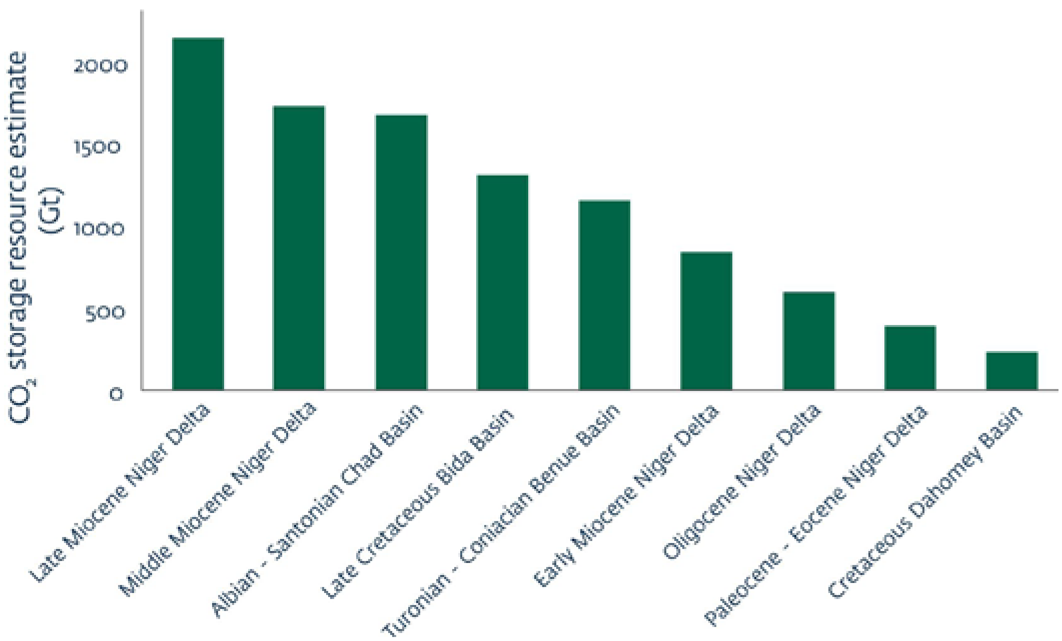


Source: Halliburton

6.2.2 Summary of Estimated Storage Resource

A CO_2 storage resource estimate was calculated for each of the key plays (Figure 6.4), following the methodology of The U.S. Carbon Storage Atlas (US DOE 2015). The estimate was adjusted using available net-to-gross values. This method was preferred given the large degree of variability in data availability from each basin, and providing a consistent methodology with which to compare each play. This simplistic, volumetric approach to calculation of storage potential is likely to significantly overestimate the available resource compared to a pressure-limited (dynamic) resource calculation. The Niger Delta Miocene plays have the highest storage resource. This, combined with their relatively low uncertainty and known ability to trap hydrocarbons make plays of this age a good candidate for further study. Beyond this, the Cretaceous stratigraphy of the Benue Basin may be of interest for further study to better determine overall storage resource and geological risk due to proximity to CO_2 source locations.

Figure 6.4. Comparative CO_2 resource estimate across all Nigerian CO_2 storage plays. The mid range storage resource value using a storage efficiency factor of 2.0% is presented (see section 5.5.3 and Box 5.4 for methodology).



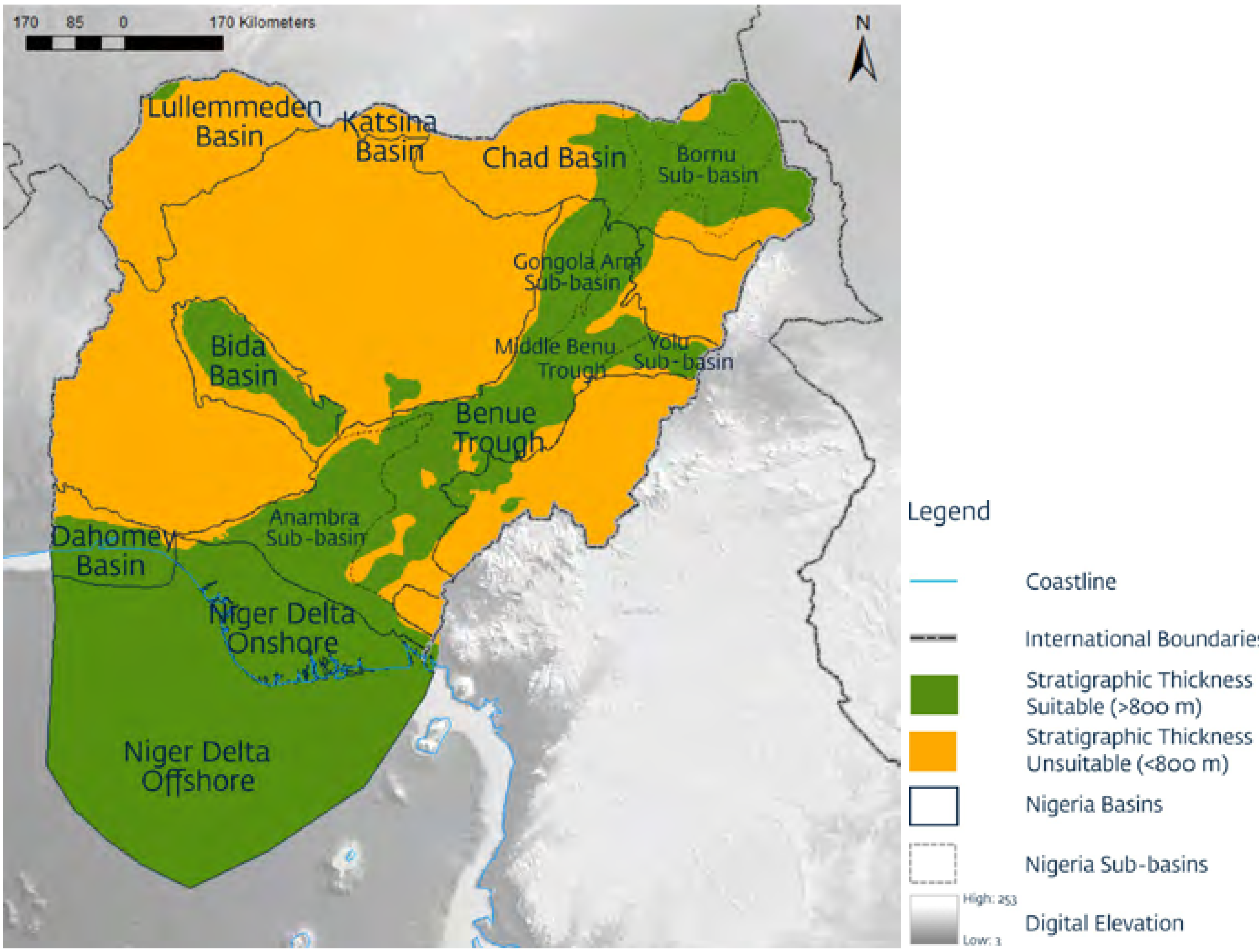
Source: Halliburton

6.3 Regional Screening for CO_2 Storage Potential in Nigeria

A regional screening assessment (see Appendix 2 for methodology) demonstrates which basins in Nigeria hold potential for CO_2 storage based on three key parameters which form the cut-off limits for the most fundamental aspects in order for a storage reservoir to work (Section 5.2):

- Depth-related pressure (sediment thickness): basins with less than 800 m (Figure 6.5a) sedimentary thickness are deemed unsuitable as they will not have the pressure regime required to achieve CO_2 storage in a supercritical state (see Section 5.2 and Box 5.1).
- Depth-related temperature: using geothermal gradient, surface temperature and depth maps are used to assess which stratigraphy in a basin could store CO_2 in a supercritical state. Figure 6.5b shows where the depth is too shallow, borderline shallow, suitable or too deep at over 3000 m. Below 3000 m effective storage decreases and costs of injection increases (Eccles et al., 2009). Hence a CO_2 storage depth window is found in the range of 800 m to 3000 m based on physical properties and economic (drilling depth) factors. For this study an optimal 800-2000 m is considered in the CO_2 play screening assessment.
- Present-day tectonism: basins which are tectonically stable are more favorable for CO_2 storage since this reduces the risk of seal damage. Although minor tremors have been recorded (probably associated with movement along the Romanche Fracture zone and the Cameroon Volcanic Line), Nigeria sits along an otherwise passive margin within the Southern Atlantic Ocean. The entire region is seismically quiescent (Figure 6.5c) with no area screened out.

Figure 6.5a. Regional screening assessment for basins with greater than 800 m stratigraphic thickness that is needed to achieve the minimum standard hydrostatic pressure gradient required to reach the threshold for CO_2 to be stored in a supercritical state.



Source: Halliburton

Figure 6.5b. Regional screening for subsurface temperature conditions required to achieve storage of CO_2 in a supercritical state.

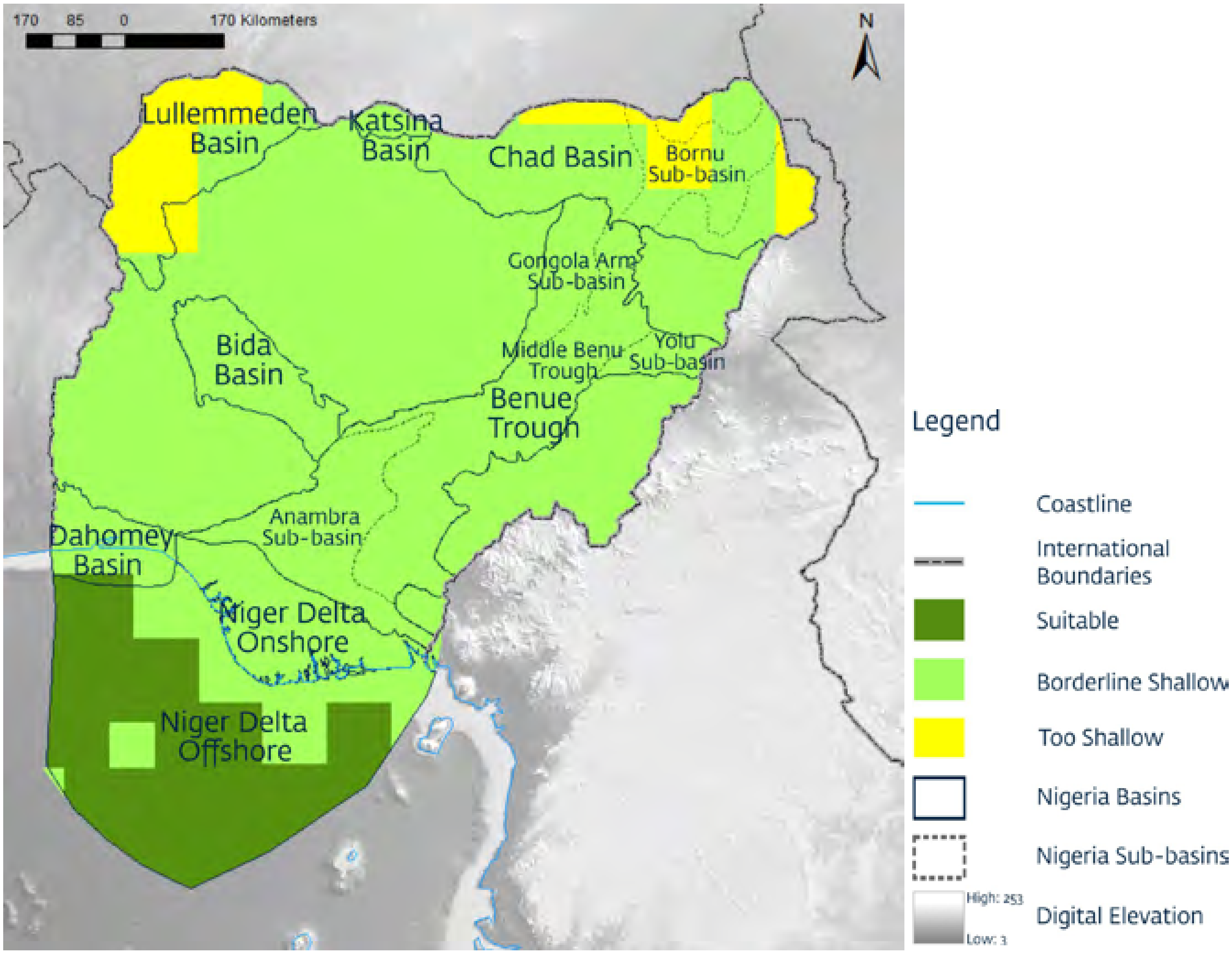


Figure 6.5c. Regional screening assessment for tectonic activity, along with basin outlines.

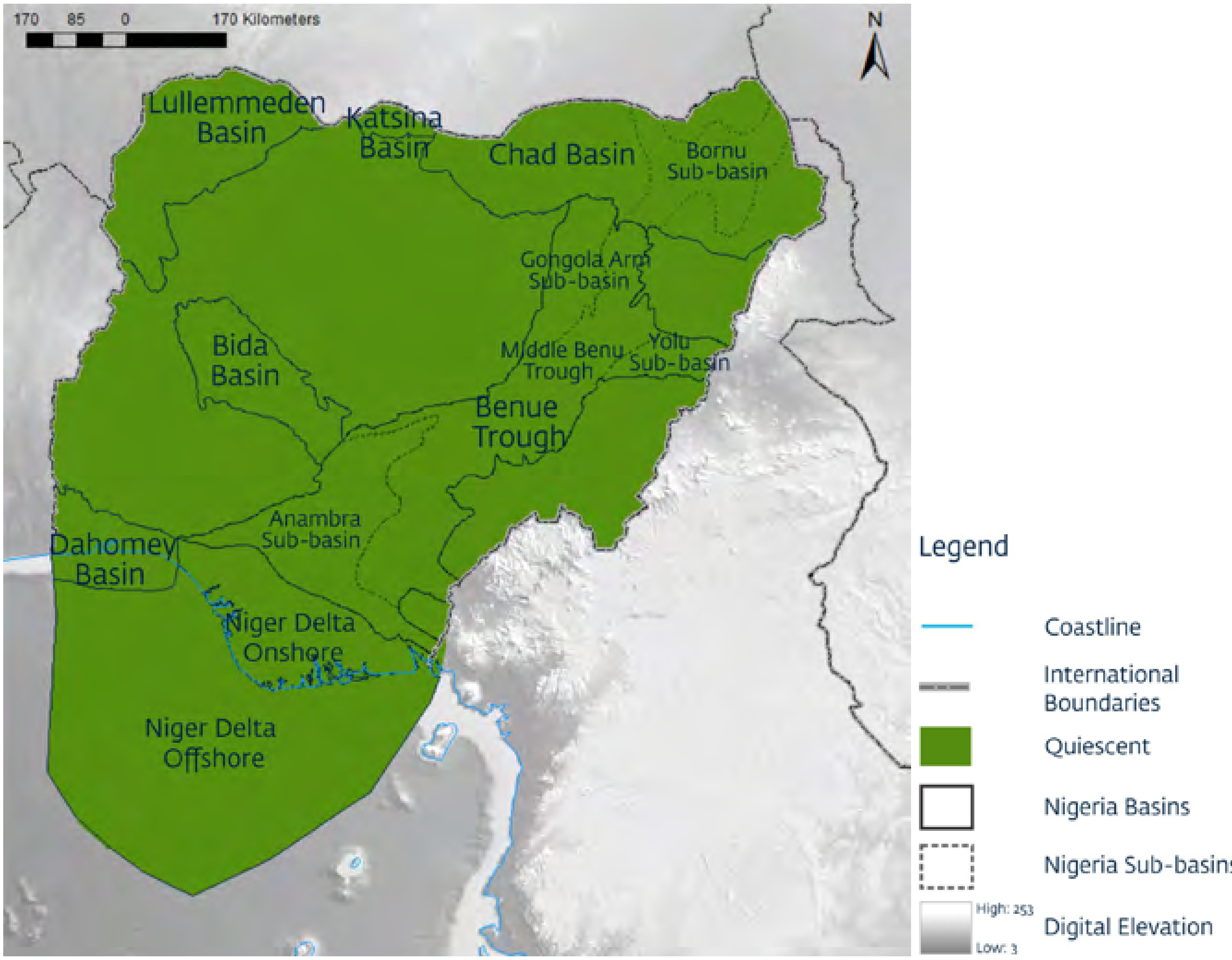
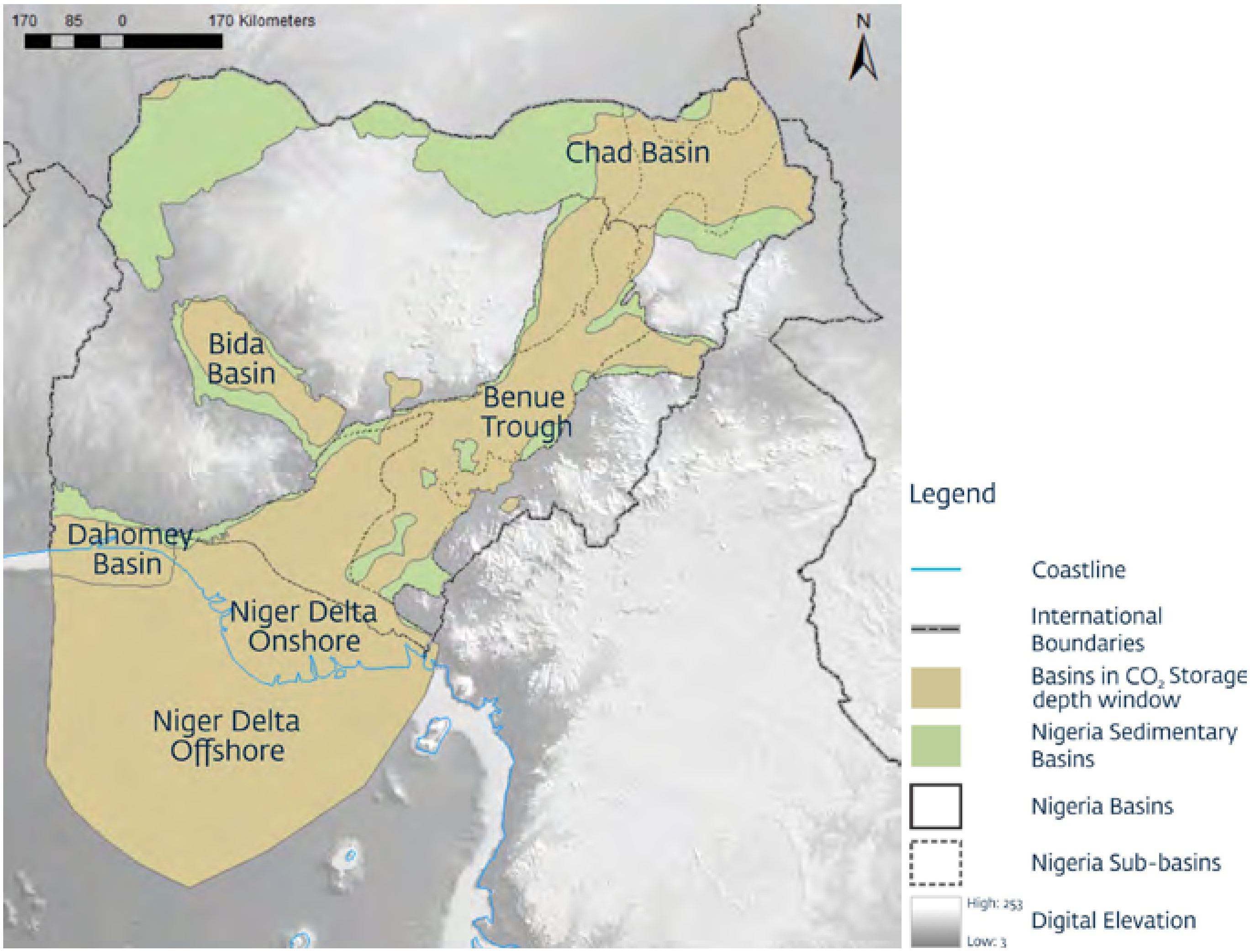


Figure 6.5d. Five sedimentary basins of Nigeria identified to have potential to store subsurface CO_2, based on regional screening criteria.



Source: Halliburton

Based on outputs from the above criteria (Figure 6.5a-c), five sedimentary basins of Nigeria show potential to store subsurface CO_2 (Figure 6.5d):

1. Niger Delta (onshore and offshore)
2. Dahomey Basin
3. Benue Trough
4. Bida Basin
5. Chad Basin

The key plays found for each basin are indicated in table 6.1 and are presented in more detail in sections 6.4-6.8

Table 6.1 Summary of key plays in this Atlas

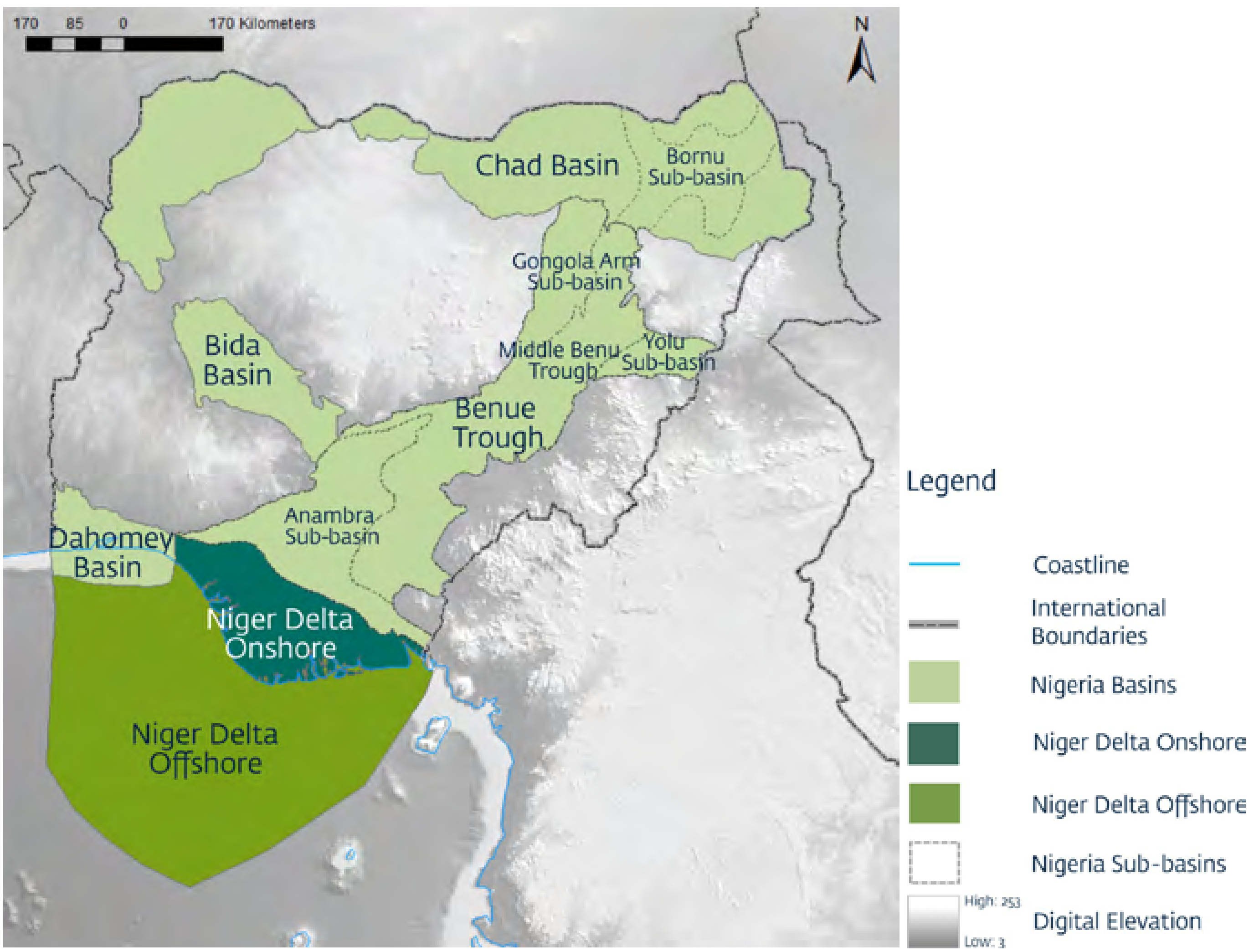
Number	Basin/Play	Play Element	Formation	Age	Lithology
1a	Niger Delta Miocene	Seal	Akata Formation	Miocene	Shallow to deep marine shales
		Reservoir	Agbada Formation	Miocene	Deltaic and deep-marine sandstones
1b	Niger Delta Oligocene	Seal	Akata Formation	Oligocene	Shallow to deep marine shales
		Reservoir	Agbada Formation	Oligocene	Deltaic and deep-marine sandstones
1c	Niger Delta Paleocene-Eocene	Seal	Akata Formation	Eocene	Shallow to deep marine shales
		Reservoir	Agbada Formation	Paleocene-Eocene	Deltaic and deep-marine sandstones
2	Dahomey Basin Early-Middle Cretaceous	Seal	Afowo Formation	Cenomanian-Santonian	Shallow to deep-marine shales
		Reservoir	Ise/ Afowo Formation	Barremian-Coniacian	Continental and marine sandstones
3a	Chad Basin Pliocene	Seal	Chad Formation	Pliocene-Pleistocene	Lacustrine shales
		Reservoir	Chad Formation	Pliocene	Lacustrine sandstones
3b	Chad Basin Early-Middle Cretaceous	Seal	Gongila/ Fika Shale Formation	Turonian-Santonian	Shallow to deep-marine shales
		Reservoir	Bima/ Gongila Formation	Albian-Turonian	Continental and shallow marine sandstones
4	Benue Trough Early-Middle Cretaceous	Seal	Unknown	Cenomanian-Santonian	Shallow to deep-marine shales
		Reservoir	Bima/ Yolde Formation	Albian-Coniacian	Continental and shallow marine sandstones
5	Bida Basin Late Cretaceous	Seal	Patti/ Nsukka Formation	Campanian-Maastrichtian	Shallow to deep-marine shales
		Reservoir	Lokoja/ Bida Formation	Coniacian-Santonian	Continental and shallow marine sandstones

6.4 Niger Delta Plays 1a-c

The Niger Delta (Figure 6.6) is one of the most productive deltaic petroleum systems in the world, with extensive exploration for oil and gas over the past 50 years. Exploration focus was initially onshore, but this shifted offshore, then to the deep offshore by the late 1990s. Onshore fields are therefore more likely to contain older wells which may have containment vulnerability and negatively affect containment of CO_2 in depleted oil and gas fields.

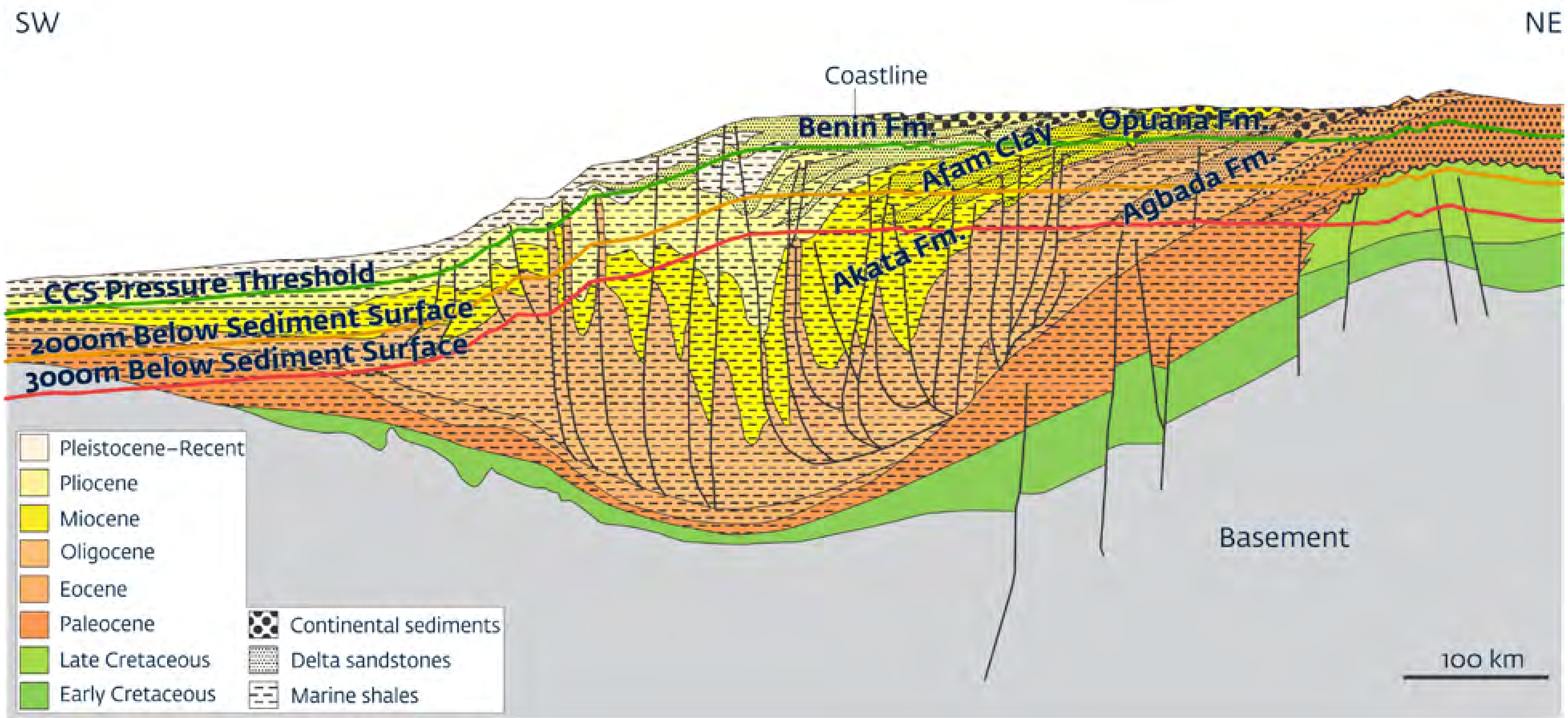
Over 12,000 m of sediments are deposited in the Niger delta, composed of three diachronous siliciclastic units: the deep-marine pro-delta Akata Group, the shallow-marine delta-front Agbada Group and the continental, delta-top Benin Group (Figure 6.7). The basin sits in the Ondo, Edo, Delta, Rivers, Imo, Bayelsa, Abia, Akwa Ibom and Anambra states. There is significant structural complexity due to growth faulting and therefore, fault containment risk will be of key concern in this basin, particularly in re-pressurization of depleted fields or untested saline aquifers. Most of the main Cenozoic structural and stratigraphic traps within the delta system have now been explored, which provides more insight into CO_2 storage potential.

Figure 6.6. Location of the Niger Delta



Source: Halliburton

Figure 6.7. A cross-section of the Niger Delta showing main sedimentary units and major structural features. Reservoirs deeper than 800 m but above 3000 m (the economical depth limit) present a potential target for storing CO_2



Source: Modified from Haack et al. (2000)

6.4.1 Potential Reservoir-Seal Pairs

Agbada/ Agbada or Akata: the Paleocene – Pliocene deltaic sandstones of the Agbada Formation are sealed by several Paleocene – Pliocene deltaic shales (Figure 6.8). Reservoir quality is known to be high and relatively uniform across the Niger Delta. The seal risk is generally low for the Niger Delta, which is supported by the numerous wells, and hydrocarbon fields distributed across the delta. The Niger Delta is however, highly faulted and faults have been shown to be both sealing and non-sealing (Nwaiide 2022), indicating that leakage along faults should be carried as a risk in any prospect-level study. The Cenozoic deltaic systems of the Niger Delta are well understood, with good data control and therefore the screening outputs for this area have relatively low uncertainty compared with the other basins considered within this study.

6.4.2 Miocene Fairway - Play 1a

There are multiple, laterally extensive target reservoir intervals in the Miocene Agbada play (Figure 6.9a). Due to the southward progradation of the delta throughout the Miocene, a greater number of these reservoirs are distributed in the offshore. Shales for potential storage site seals are widely distributed (Figure 6.9b), but again limit the extent of the fairway to the north. The Miocene plays are less deeply buried than the Oligocene or Paleocene-Eocene plays, consequently there is a larger area of the play that falls within the preferred depth window for CO_2 storage (Figure 6.9c) compared to the older stratigraphy. Therefore, this Miocene fairway has the greatest areal extent of all the plays within the Niger Delta and is most favorable for further exploration (Figure 6.9c).

Figure 6.8. General stratigraphy of the Niger Delta with potential CO_2 storage reservoir-seal pairs identified.

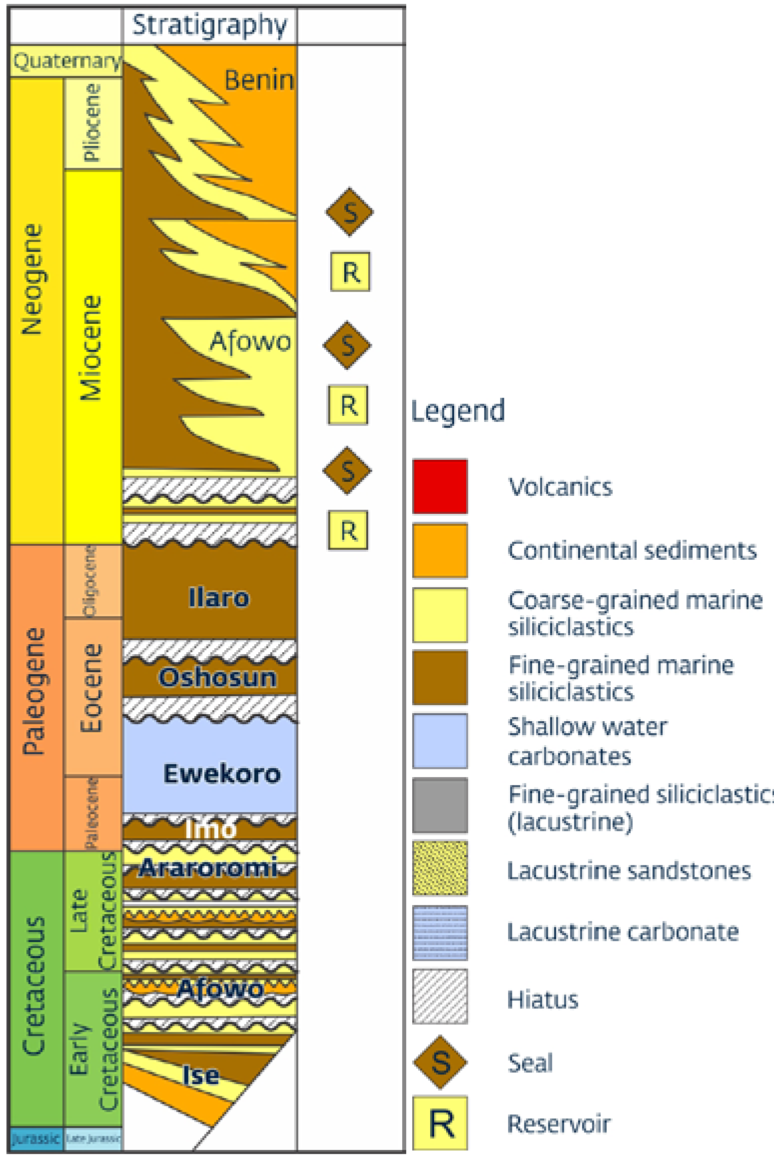


Figure 6.9a. Maximum likely preservational extent of stacked Miocene Agbada Formation sandstone reservoir in the Niger Delta.

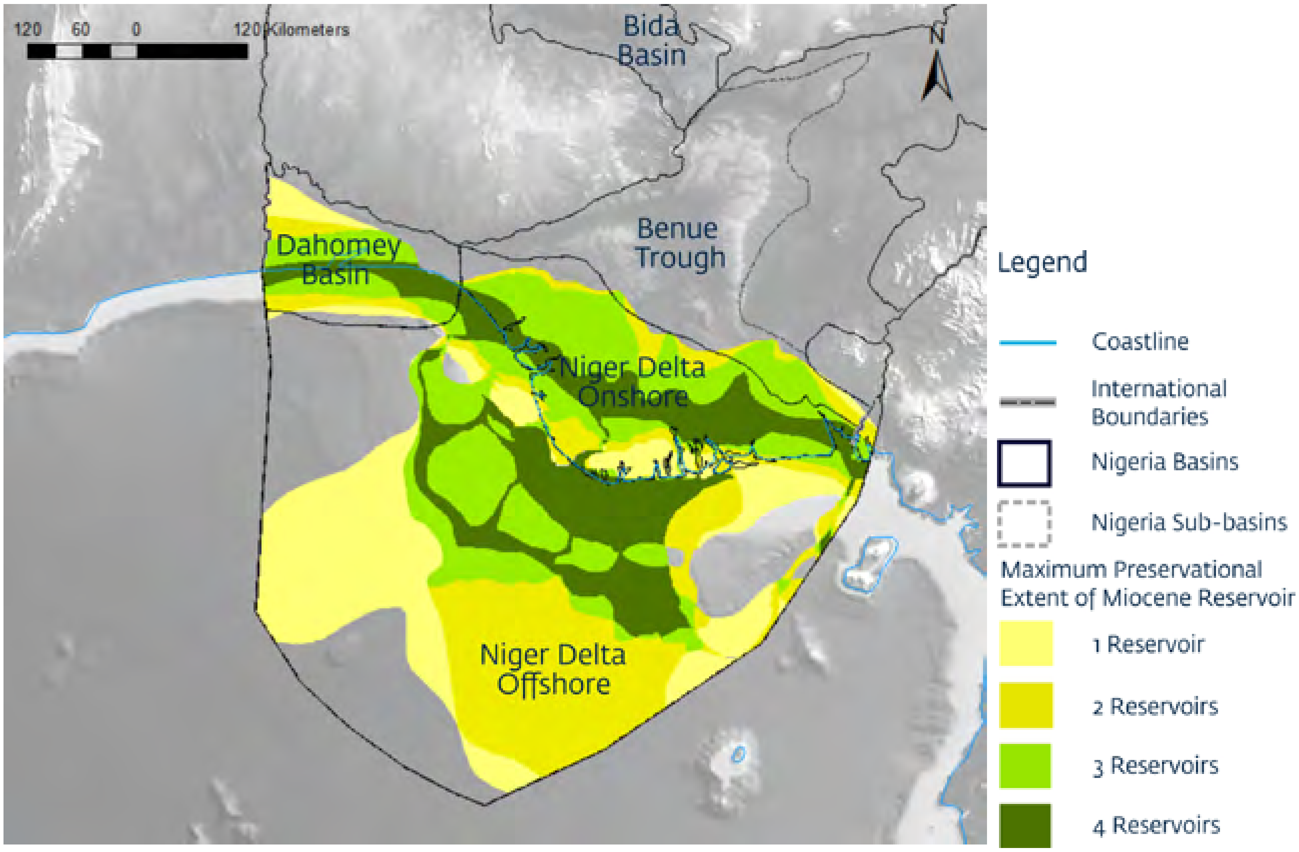


Figure 6.9b. Maximum likely preservational extent of stacked Miocene Akata Formation shale seal in the Niger Delta.

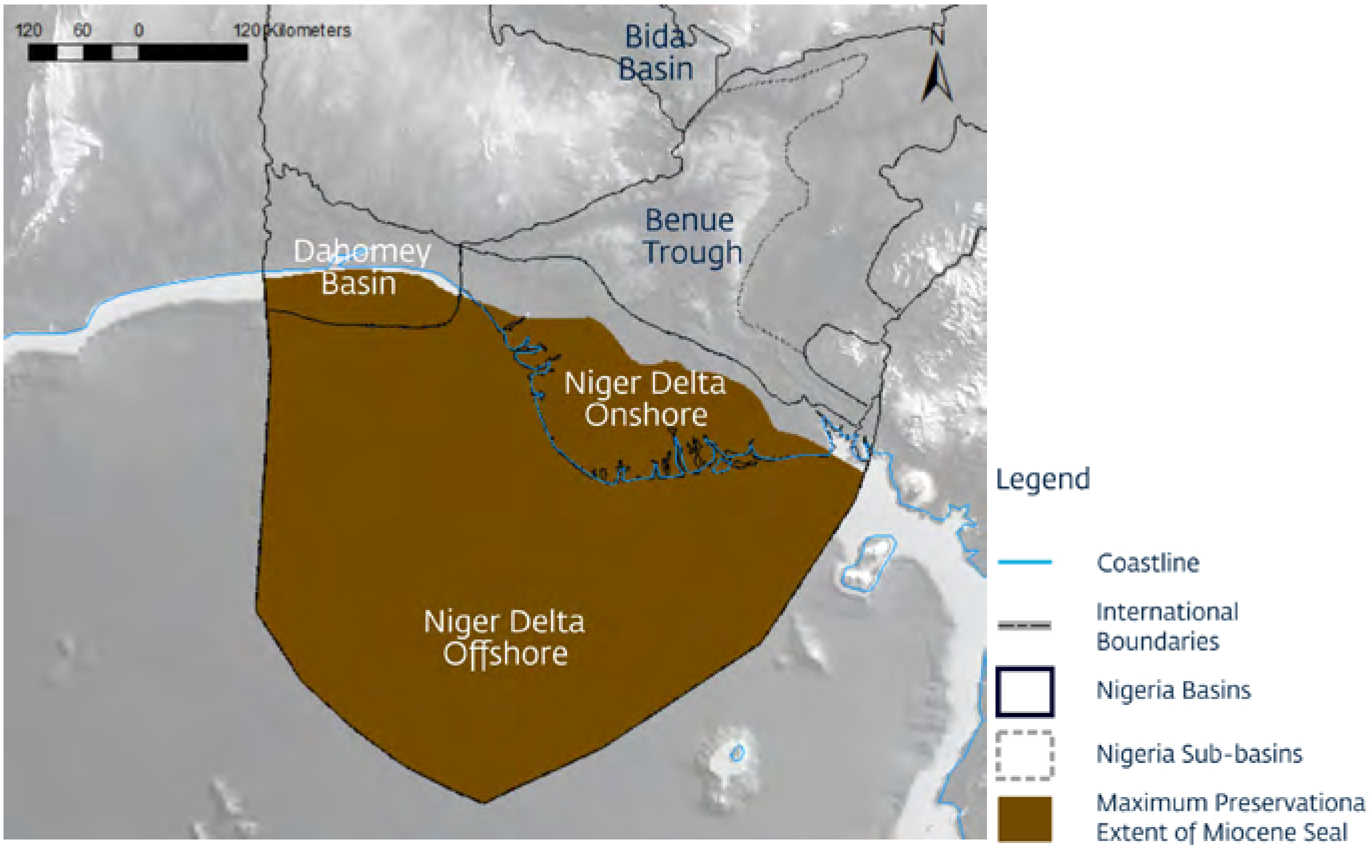
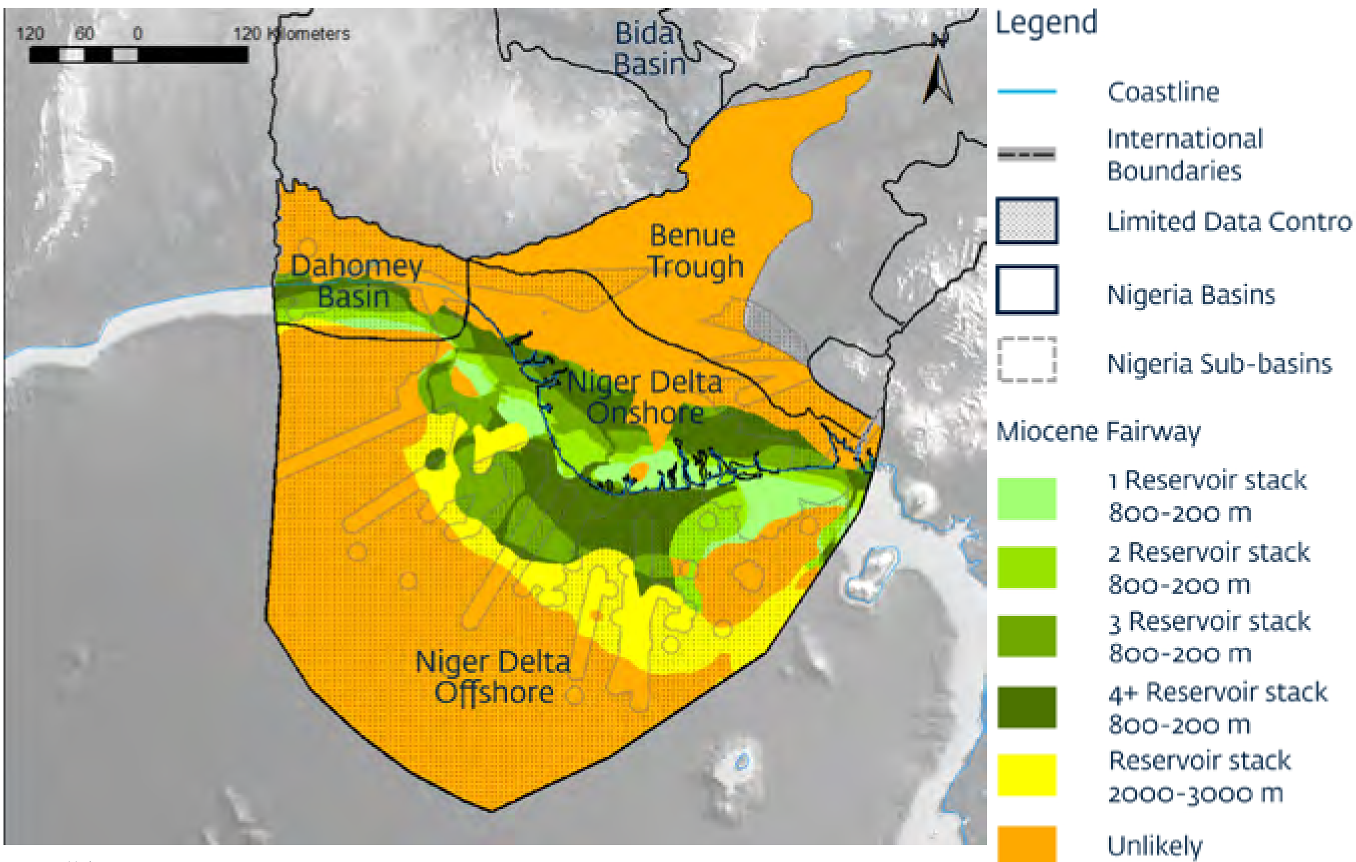


Figure 6.9c. A CCRS map illustrating the prospective fairway of the Oligocene Agbada Formation sandstone reservoir and Akata Formation shale seal in the Niger Delta. High graded areas within the fairway with numerous stacked reservoir target intervals (including overlying Oligocene-Late Miocene intervals) are delineated in shades of green. The optimal reservoir depth below surface, 800-2000 m, is indicated, along with the deeper 2000-3000 m interval. All other areas where the reservoir-seal pair is not present or is <800 m or >3000 m are indicated to be unlikely for storage. Areas with limited/no data control are also shown. These areas carry greater uncertainty in the play extent.



6.4.3 Oligocene Fairway – Play 1b

By the Oligocene epoch, the Niger Delta had prograded towards the southwest, depositing sand over a greater part of the offshore area than in the Miocene play (Figure 6.10a). The seals in this play are widely developed; however, they do not fully cover the full reservoir extent, slightly limiting the play to the northeast (Figure 6.10b). Much of the play is buried too deeply for CO_2 storage (Figure 6.10c).

Figure 6.10a. Maximum likely preservational extent of stacked Oligocene Agbada Formation sandstone reservoir in the Niger Delta

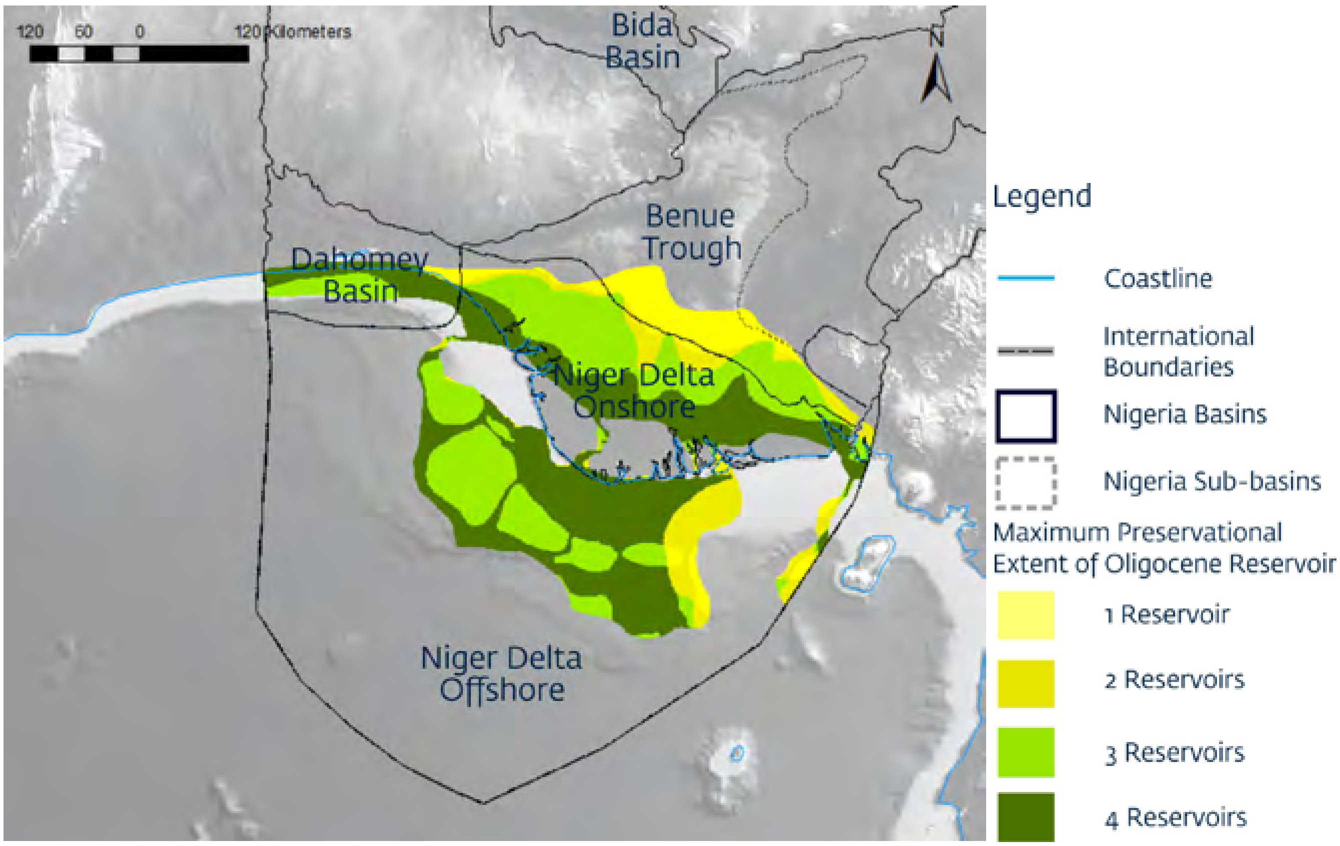


Figure 6.10b. Maximum likely preservational extent of stacked Oligocene Akata Formation shale seal in the Niger Delta.

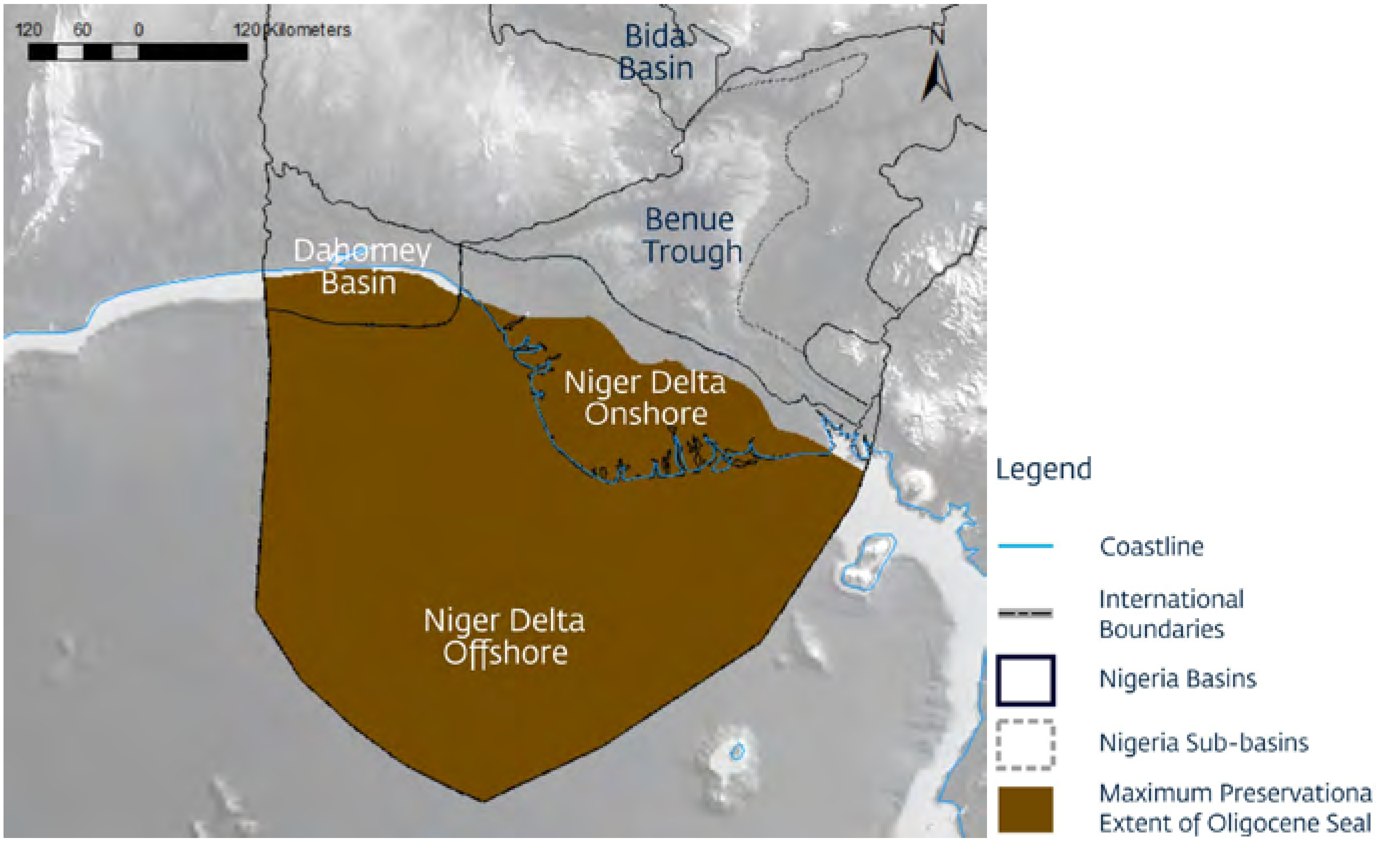
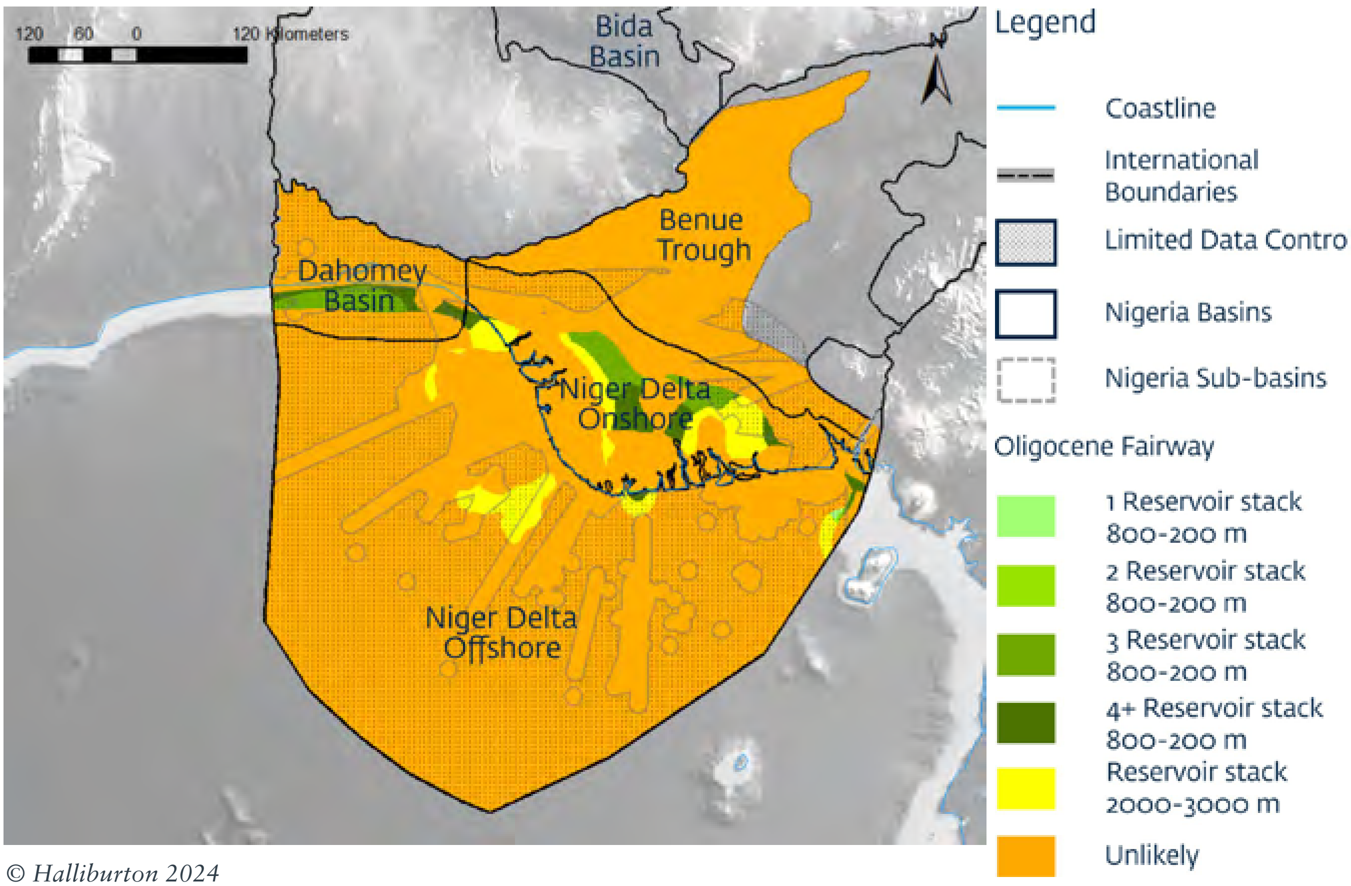


Figure 6.10c. A CCRS map illustrating the prospective fairway of the Oligocene Agbada Formation sandstone reservoir and Akata Formation shale seal in the Niger Delta. High graded areas within the fairway with numerous stacked reservoir target intervals (including overlying Oligocene-Late Miocene intervals) are delineated in shades of green. The optimal reservoir depth below surface, 800-2000 m, is indicated along with the deeper 2000-3000 m interval. All other areas where the reservoir-seal pair is not present or is <800 m or >3000 m are indicated as unlikely for storage suitability. Areas with limited/no data control are also shown. These areas carry greater uncertainty in the play extent.



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6.4.4 Paleocene-Eocene Fairway – Play 1c

During the Paleocene and Eocene, the Niger Delta coastline was located landward of its present-day position. Reservoir targets of this age are therefore largely distributed onshore (Figure 6.11a). Overlying seal formations are widely distributed across the delta (Figure 6.11b) but pinch out toward the northeast (marginally limiting the northward extent of the play). In addition, seal integrity is likely to improve towards the south, where shalier facies become more dominant. Due to thick overlying delta deposits, much of the Paleocene Eocene stratigraphy is very deeply buried (Figure 6.11c) and is therefore not in a favorable depth window for CO_2 storage. The overall extent of the storage fairway is restricted to a thin band in the southern onshore part of the mapped play (Figure 6.11c). High-graded areas within the fairway are indicated where numerous stacked Paleocene-Miocene reservoir targets are present. A storage location in one of these stacked areas could potentially have access to multiple back-up storage horizons, increasing their appeal.

Figure 6.11d shows the optimal fairway for CO_2 storage and the proximity of local CO_2 sources, showing some potential for geographically close CO_2 source and storage options.

Figure 6.11a. Maximum likely preservational extent of stacked Paleocene-Eocene Agbada Formation sandstone reservoir in the Niger Delta.

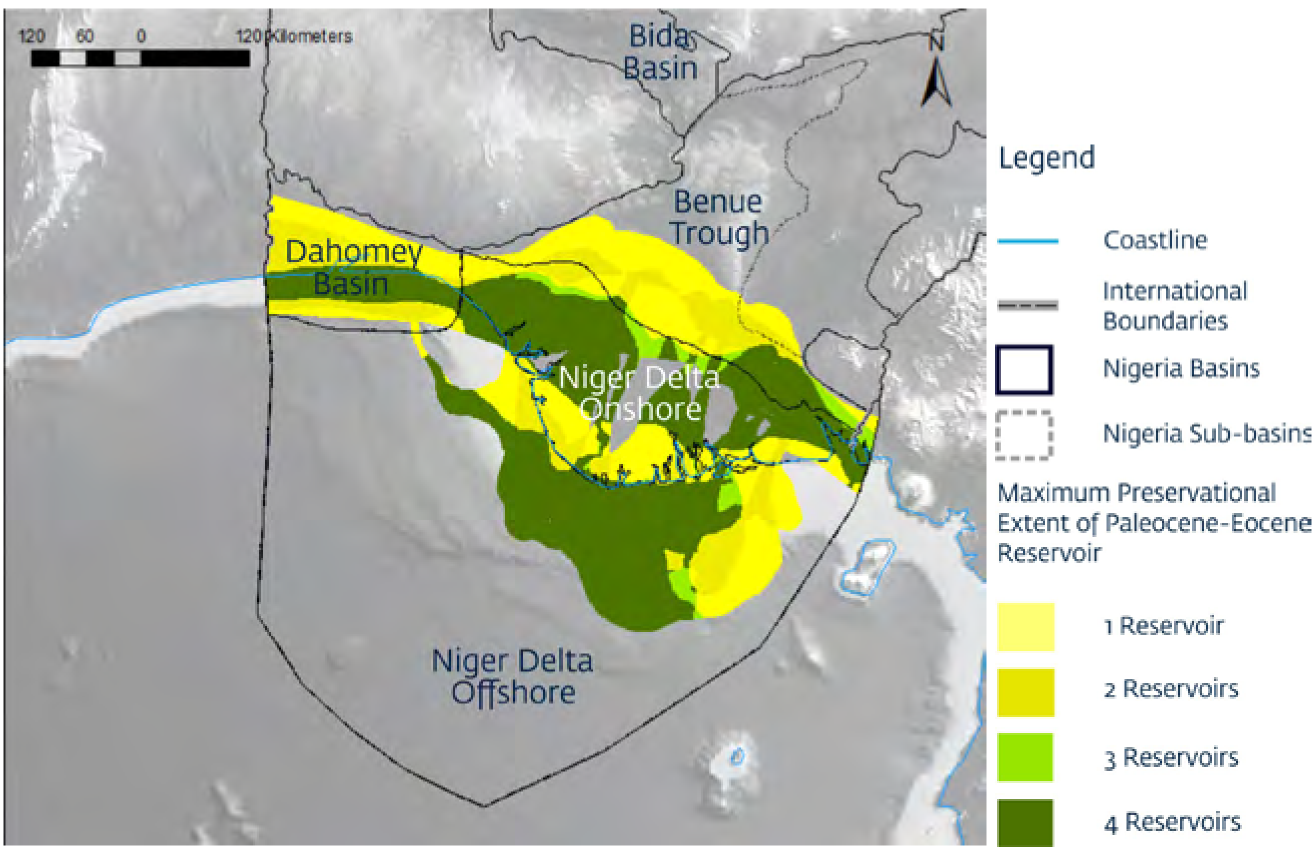


Figure 6.11b. Maximum likely preservational extent of stacked Paleocene-Eocene Akata Formation in the Niger

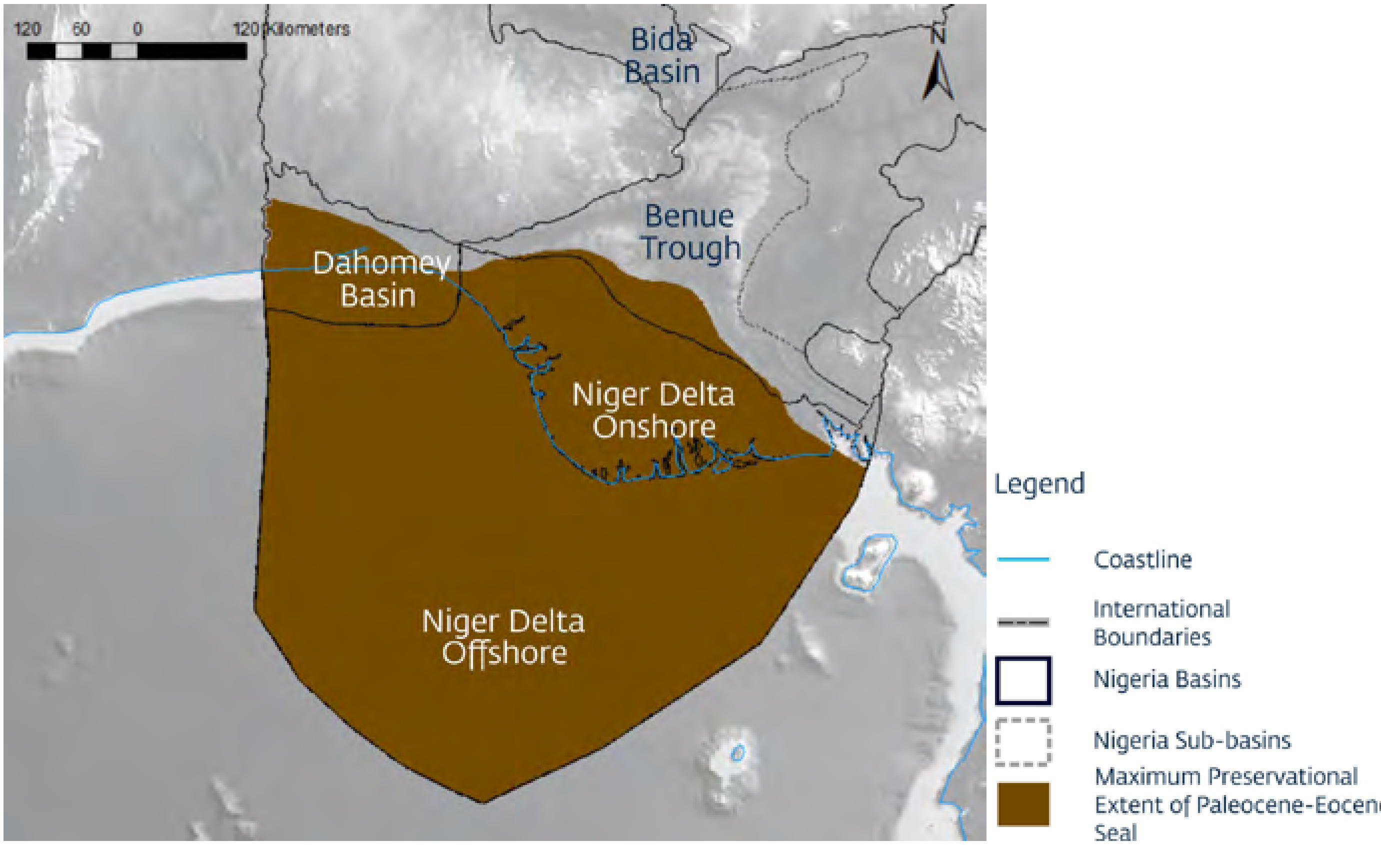


Figure 6.11c. A CCRS map illustrating the prospective fairway of the Paleocene-Eocene Agbada and Akata Formation. High graded areas within the fairway with numerous stacked reservoir target intervals (including overlying Oligocene-Late Miocene intervals) are delineated in shades of green. The optimal reservoir depth below surface, 800-2000 m, is indicated along with the deeper 2000-3000 m interval. All other areas where the reservoir-seal pair is not present or is <800 m or >3000 m are indicated as unlikely to be suitable for storage. Areas with limited/no data control are also shown. These areas carry greater uncertainty in the play extent.

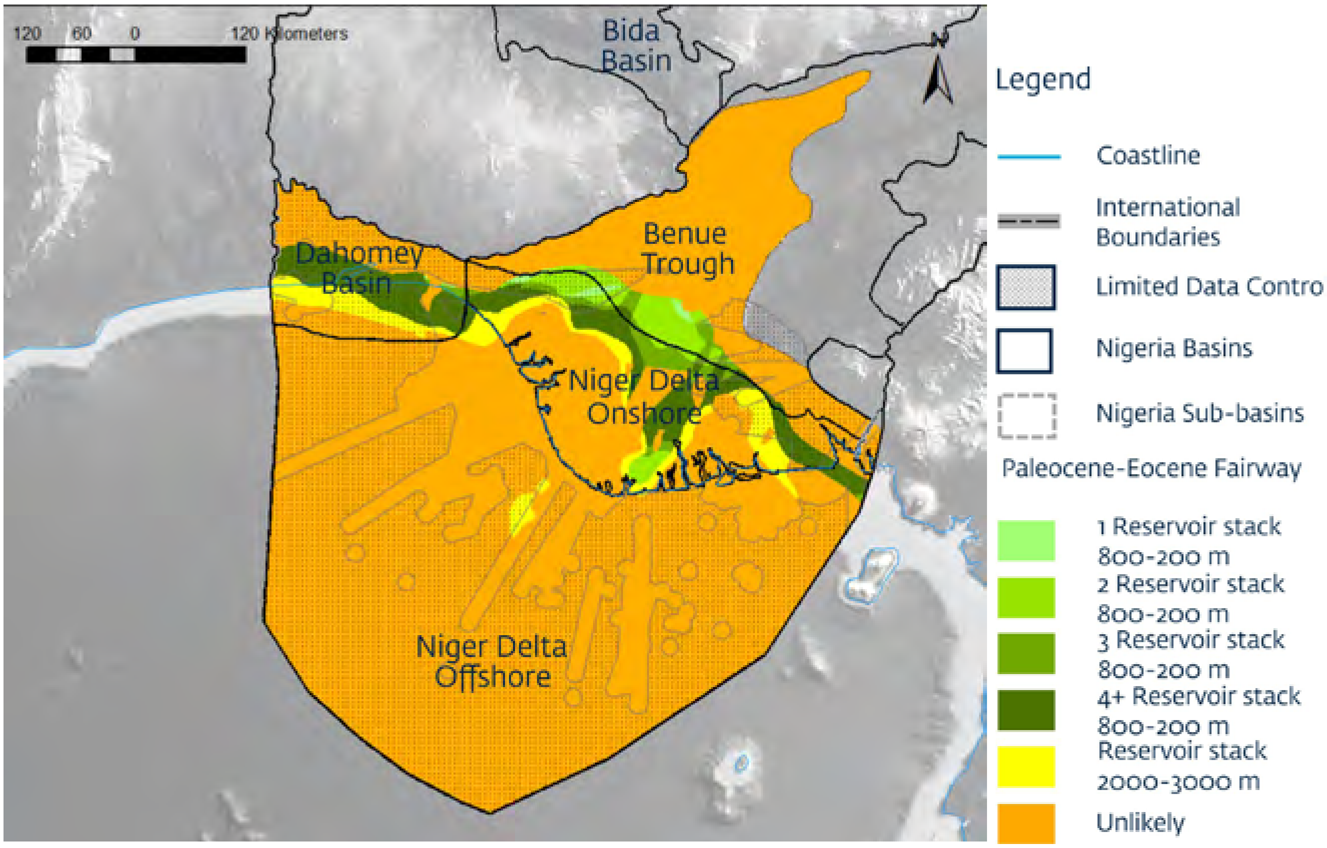
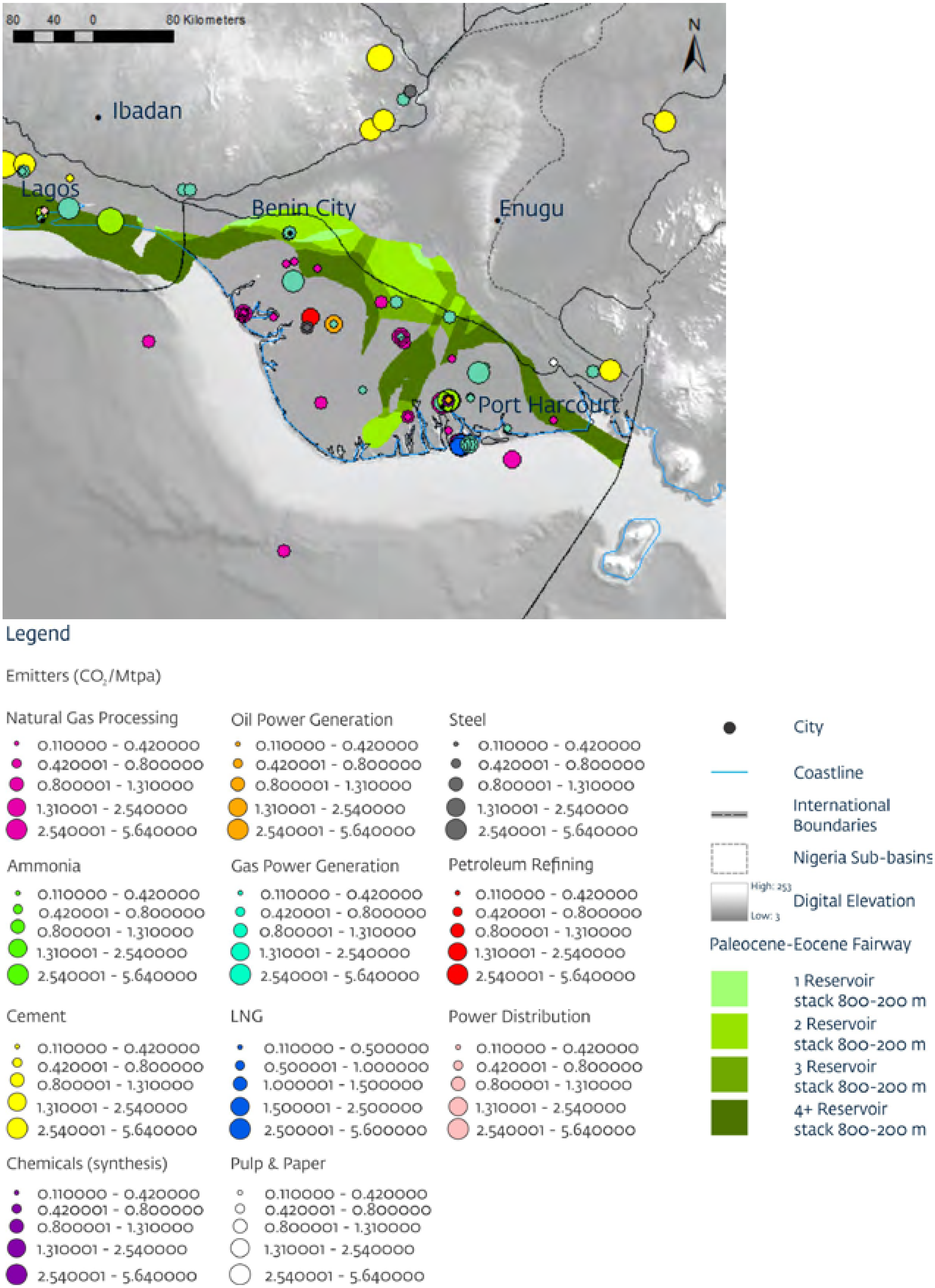


Figure 6.11d Map of the Paleocene- Eocene Fairway in the Niger Delta (delineated in green) with local CO_2 emitters.



Source: Halliburton, BCG

6.4.5 Resource

Using the volumetric calculation formula described in section 5.5.3 the estimated storage resource for the Niger Delta storage units are shown in Table 6.2

Table 6.2. Summary of the input data and resulting prospective storage resource for the Niger Delta Basin. Data from Tuttle et al. 1999, Chudi et al. 2016, Okpogo et al. 2018. N.B. Although the Niger Delta is extensively explored, data pertaining to specific ages of reservoirs is not widely available. Given the known uniformity in the Agbada Formation, similar values have been applied to all plays.

**Only net formation thickness available so no net-to-gross value applied.*

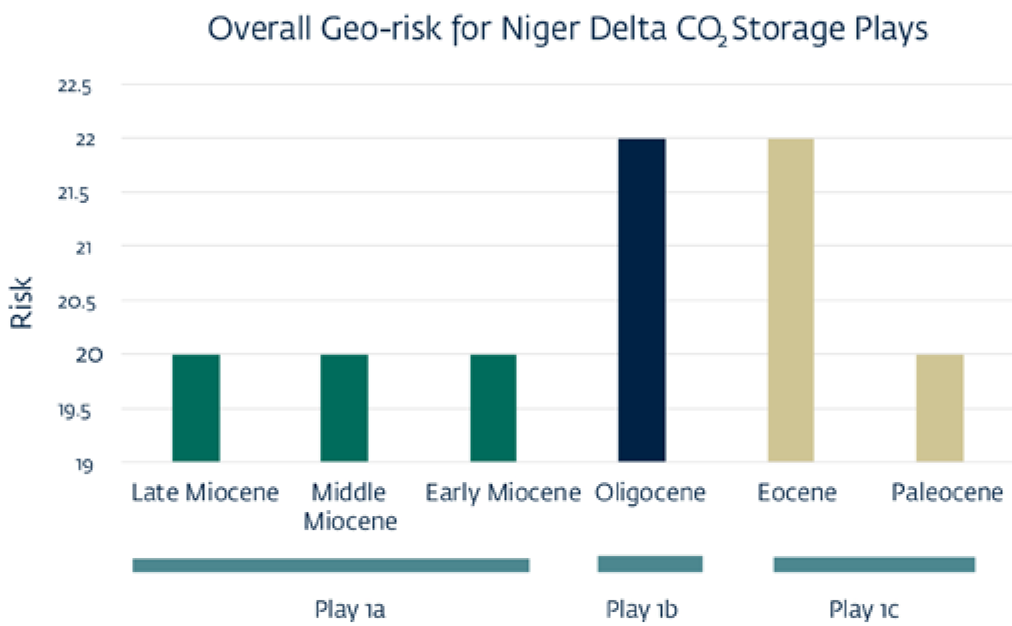
Play Name	Play Age	Average Porosity (%)	Average Reservoir Thickness (m)	Net:Gross	Fairway Area (m^2)	Prospective Storage Volume (Mt)		
						Low	Medium	High
Agbada-Agbada	Late Miocene	32	100	0.68	70,295	546,000	2,141,000	5,782,000
Agbada-Agbada	Middle Miocene	30	100	0.68	60,880	443,000	1,739,000	4,695,000
Agbada-Agbada	Early Miocene	28	50	0.68	63,829	217,000	851,000	2,297,000
Agbada-Agbada	Oligocene	17	150	0.68	25,103	155,000	609,000	1,645,000
Agbada-Akata	Eocene	27	38	1*	28,493	104,000	409,000	1,105,000
Agbada-Akata	Paleocene	28	100	0.68	19,080	130,000	509,000	1,373,000

Source: Halliburton

6.4.6 Geo-risk and SRMS Classification

Based on the geo-risk criteria outlined in section 5.4.4, the Niger Delta plays have a relative risk category as shown on Figure 6.12 with the three plays ranging between 20 and 22. The Niger Delta has the lowest risk of all plays assessed in Nigeria with the Miocene showing the least risk. The SRMS classification, using the decision-based flow chart outlined in section 5.3, defines the Niger Delta Basin saline aquifer formations as Undiscovered, Prospective Sequence Plays. There are also hydrocarbon and depleted hydrocarbon fields in the Niger Delta (see section 6.4) and therefore, by virtue of the presence of wells, place the classification of these potential storage sites as a Discovered, Contingent Storage Resources, Development not Viable.

Figure 6.12. A comparative risk graph that shows the cumulative risk for all Niger Delta plays based on the geo-risk criteria outlined in section 5.5.4

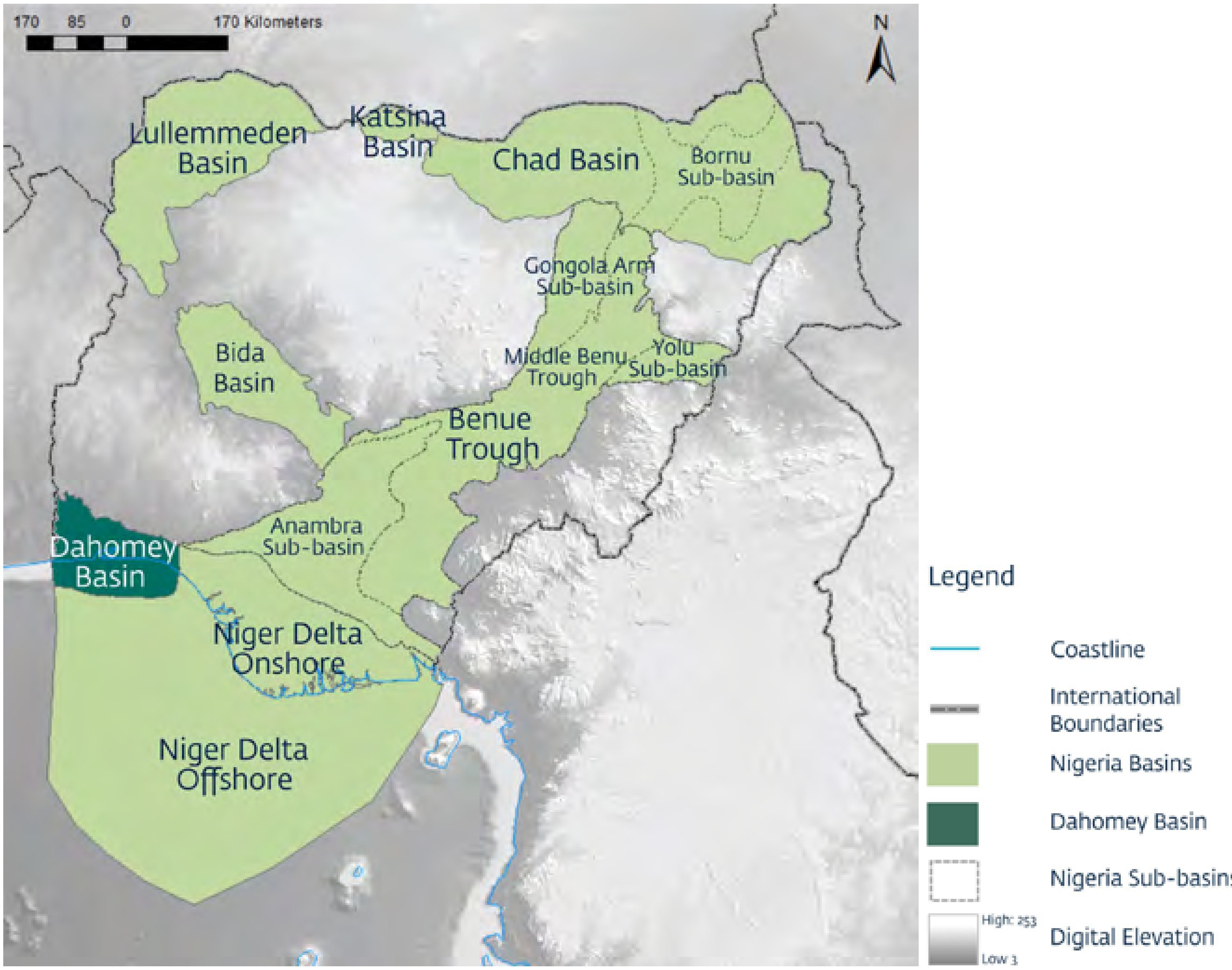


Source: Halliburton

6.5 Dahomey Basin – Play 2

The Dahomey Basin (Figure 6.13) has moderate data coverage since hydrocarbon exploration activities started in 1908 in the Araromi area, Ondo State. Several drilling campaigns in the basin over the following century encountered bituminous layers but without evidence of a working trap. However, the trapping potential of the Dahomey Basin was confirmed by the discovery of the Aje and Ogo offshore fields in 2009 and 2013, respectively (Falufosi and Osinowo 2021), within Cretaceous age sediments. Much of the data in the basin is not publicly available which adds to the uncertainty of the CO_2 storage fairway. The basin sits in the states of Ogun, Lagos and Ondo.

Figure 6.13. The location of the Dahomey Basin.

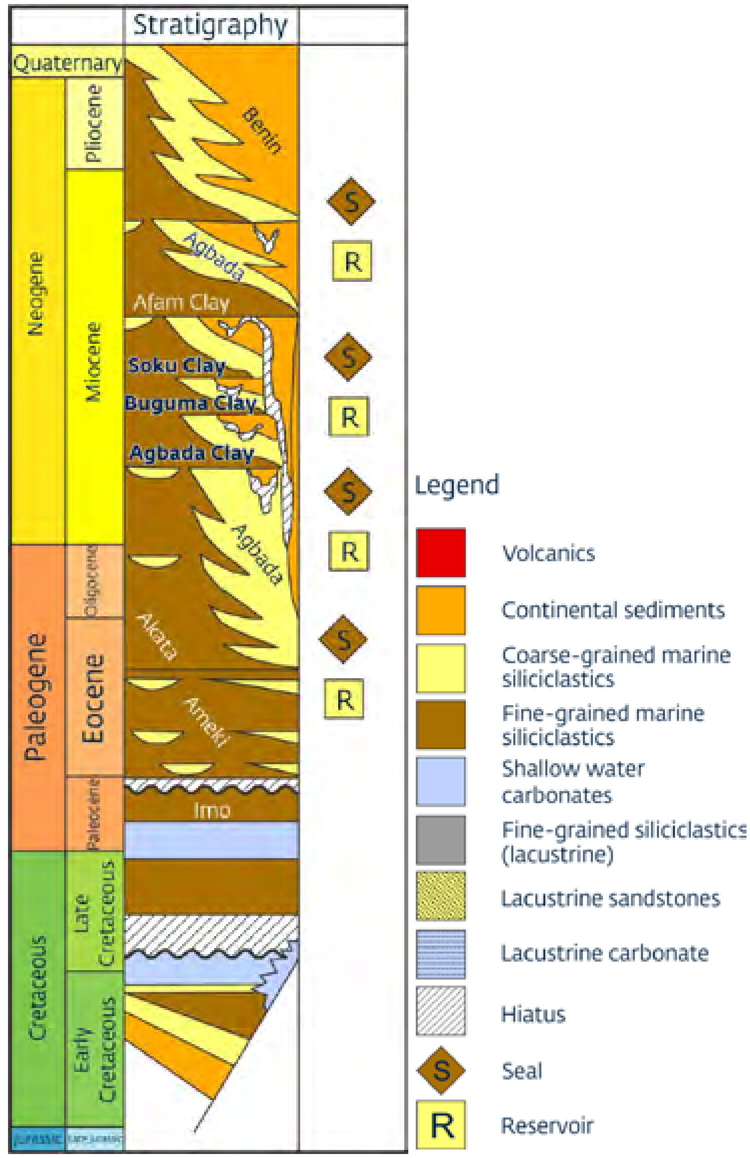


Source: Halliburton.

6.5.1 Potential Reservoir-Seal Pairs

Ise and Afowo/ Araromi: the Valanginian – Maastrichtian sandstones of the Ise and Afowo Formations form a reservoir-seal pair with the marine shales of the Maastrichtian upper Afowo and Araromi Formations (Figure 6.14). The Ise/Afowo sands are proven reservoirs in the Aje and Ogo fields and have good reservoir properties (Abubakar and Ahmadov 2022, Nwaiide 2022). The presence of oil fields in the offshore sector of the Dahomey basin demonstrates the effectiveness of the interbedded Afowo seal. The overlying Araromi shales are also laterally extensive. Parts of the Ise Formation were deposited in a syn-rift phase so some faulting may be expected. Overall, the plays in the basin are relatively well understood. Given the recent timing of hydrocarbon discoveries in this basin, none of the oil and gas fields are likely to be depleted and ready for storage currently or in the near future, thus storage is reliant on saline aquifer opportunities. There are also Paleocene age carbonates of the Ewekoro Formation; however, little is known about the porosity system and injectivity potential of the rocks (Adamolekun et al. 2022). In addition, the younger formations are not expected to be buried deeply enough to support supercritical CO_2 storage.

Figure 6.14. General stratigraphy of the Dahomey Basin with potential CO_2 storage reservoir-seal pairs identified.



6.5.2 Cretaceous Fairway Play 2

The Dahomey Basin has known hydrocarbon plays and therefore has a high certainty of working reservoir–seal pairs for the storage of buoyant fluids in the basin.

The late syn-rift age continental to marine sandstones of the basin are likely to have a high lateral extent, with sands transgressing across the basin (Figure 6.15a), as are the overlying Cretaceous marine shale sealing formations (Figure 6.15b). However, the sedimentary succession pinches out towards the north such that Cretaceous reservoir horizons are not sufficiently buried in the northern part of the basin (below 800 m), and the depth of the play increases rapidly into the offshore area due to a basinward thickening of the sedimentary overburden. This puts much of the Cretaceous interval outside of the preferred depth window for CO_2 storage. Therefore, the high-graded fairway (Figure 6.15c) and available storage resource volume (Table 6.3) in the basin is relatively small compared to other basins considered in this Atlas.

Figure 6.15a. Maximum likely preservational extent of stacked Early-Middle Cretaceous Ise/ Afowo formation reservoir in the Dahomey Basin.

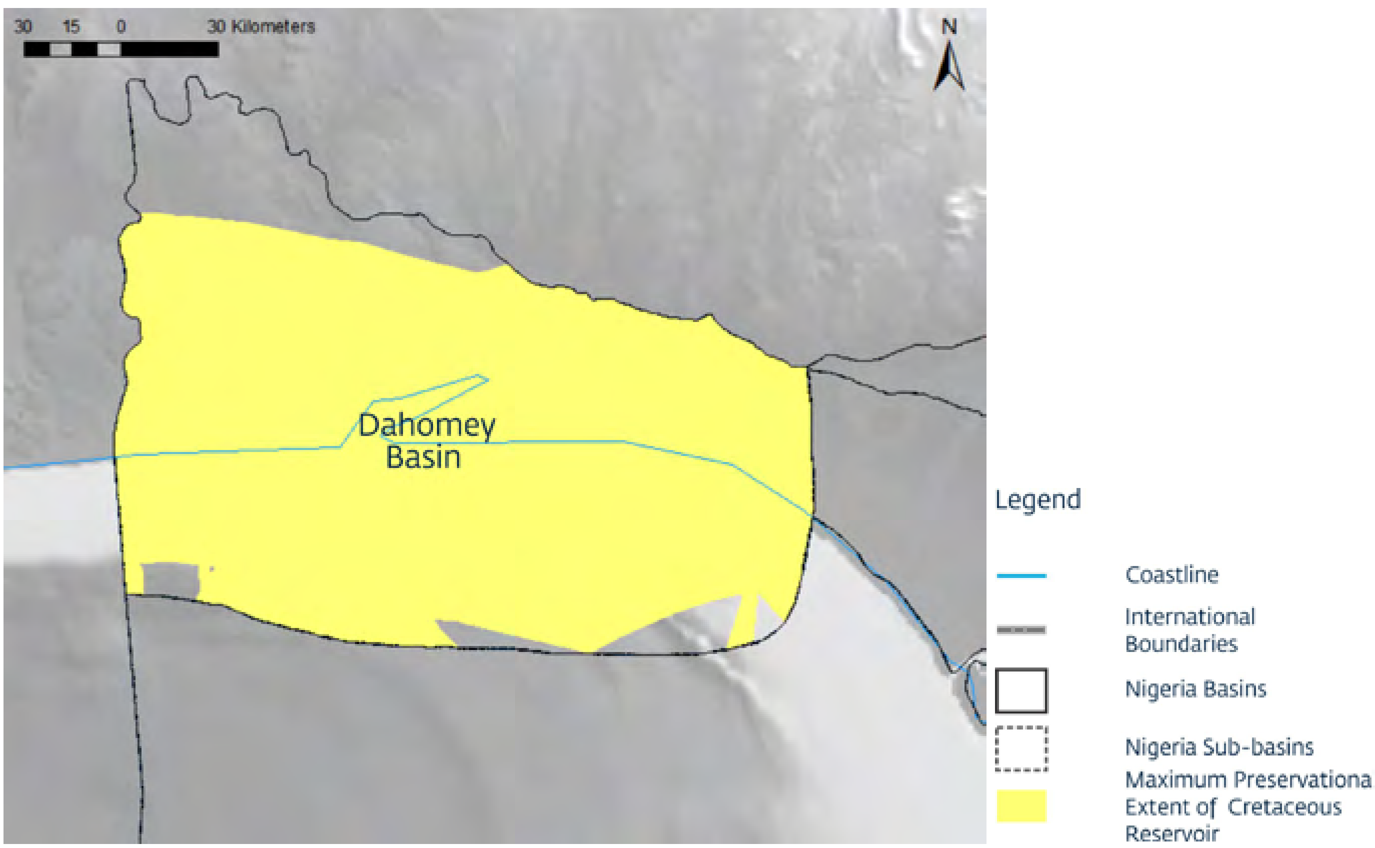


Figure 6.15b. Maximum likely preservational extent of stacked Early-Middle Cretaceous Afowo formation shale in the Dahomey Basin.

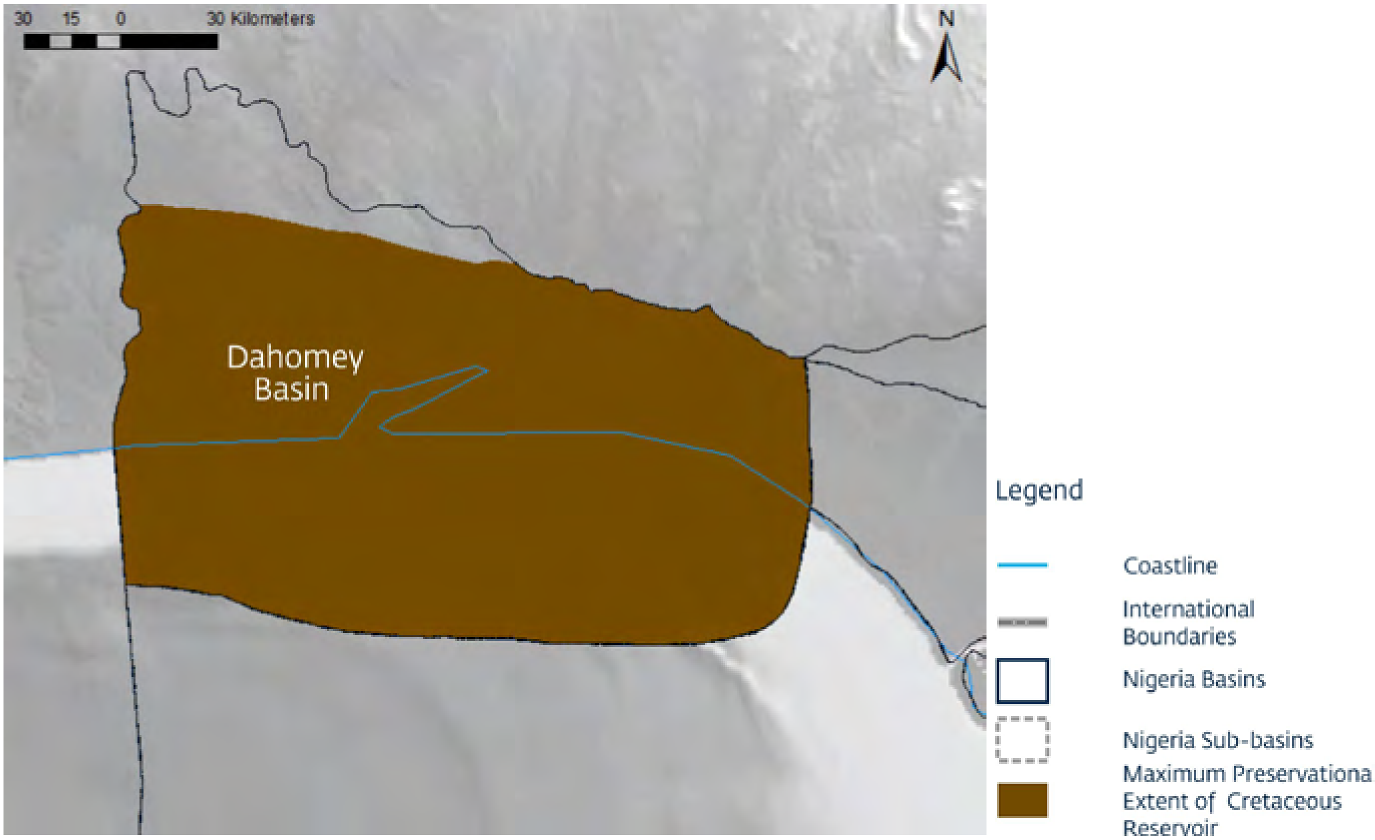
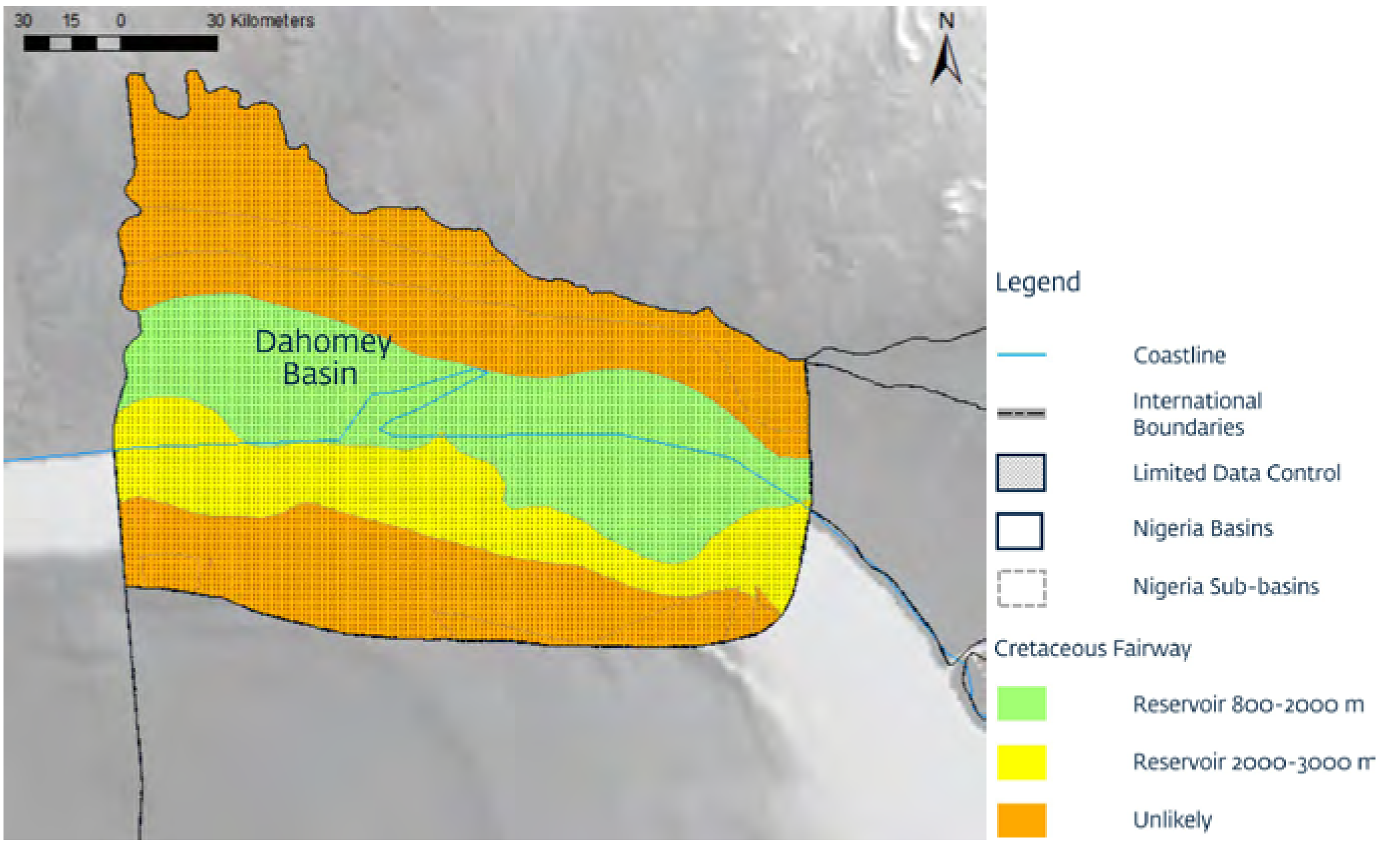


Figure 6.15c. A CCRS map illustrating the prospective fairway of the Early-Middle Cretaceous Ise/ Afowo Formation sandstone reservoir and Afowo Formation shale seal in the Dahomey Basin. The optimal reservoir depth below surface, 800-2000 m, is indicated along with the deeper 2000-3000 m interval. All other areas where the reservoir-seal pair is not present or is <800 m or >3000 m are indicated as unlikely to be suitable for storage. Areas with limited/no data control are also shown. These areas carry greater uncertainty in the play extent.



6.5.3 Resource

Using the volumetric calculation formula described in section 5.5.3 the estimated storage resource for the Dahomey Basin storage units are shown in Table 6.3.

Table 6.3. Summary of the input data and resulting prospective storage resource for the Dahomey Basin. Data from Abubakar and Ahmadov 2022, Bata et al. 2017, Adamolekun 2023.

Play Name	Play Age	Average Porosity (%)	Average Reservoir Thickness (m)	Net:Gross	Fairway Area (m^2)	Prospective Storage Volume (Mt)		
						Low	Medium	High
Abeokuta Group	Cretaceous	18	150	0.8	7,978	62,000	241,000	651,000

Source: Halliburton

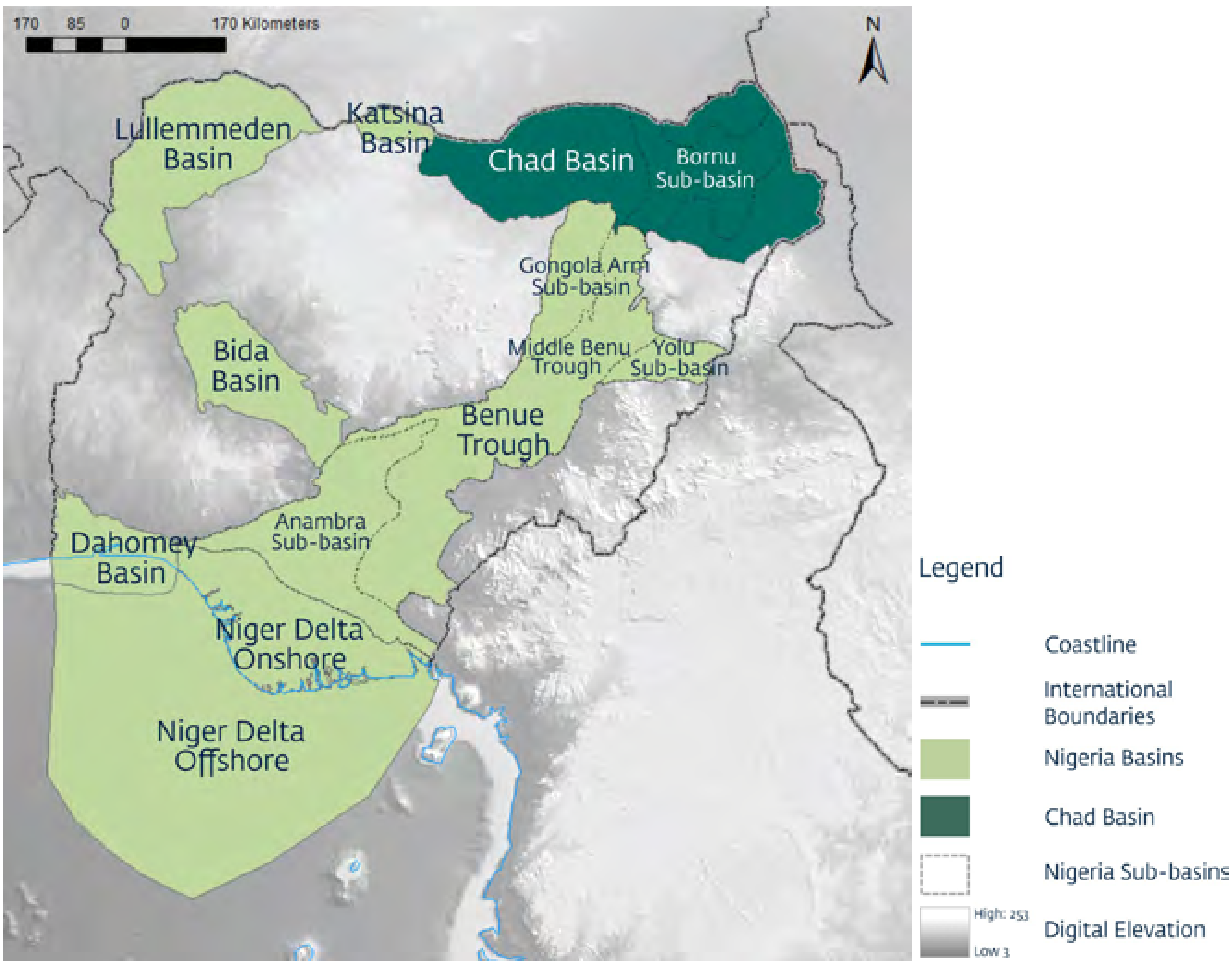
6.5.4 Geo-risk and SRMS Classification

The geo-risk criteria outlined in section 5.4.4 indicate that the Dahomey Basin carries a risk index of 24 for the Cretaceous Play. Other formations were assessed for their geo-risk but are likely too shallow for supercritical storage of CO_2. The SRMS classification using the decision-based flow chart outlined in section 5.3 defines the Dahomey Basin saline aquifer formations as Undiscovered, Prospective Sequence Plays. There are also hydrocarbon and depleted hydrocarbon fields in the Dahomey Basin and therefore, by virtue of the presence of wells, will place the classification of these potential storage sites as a Discovered, Contingent Storage Resources, Development not Viable.

6.6 Chad Basin – Play 3a-b

The Chad Basin (Figure 6.16) is a frontier basin with low data coverage. The first exploration activities in the Nigerian Chad Basin occurred between 1970s-1990s (Olabode et al. 2015) and was focused on the Upper Cretaceous sediments (Hamza and Hamidu 2011). Other formations are poorly covered by data (e.g. Cenozoic Kerri-Kerri Formation) whilst others were not penetrated by drilling (e.g. the Lower Cretaceous of the Bima Formation). The identified Cretaceous plays are within the CO_2 storage depth window, with over 5000 m of total sediments recorded (Olabode et al. 2015). The Chad Basin sits in the states of Jigawa, Yobe, Bornu, and Bauchi.

Figure 6.16. Location of the Chad Basin



Source: Halliburton

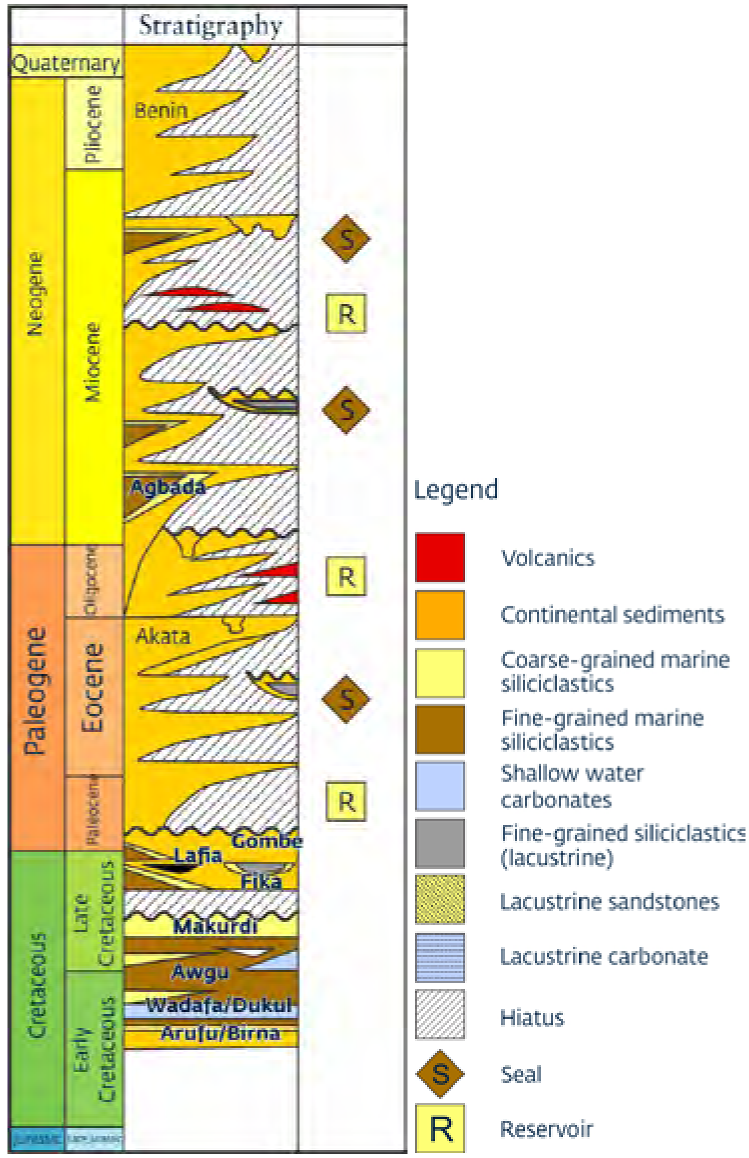
6.6.1 Potential Reservoir-Seal Pairs

Bima/ Gongila Formation: the Aptian – Albian Upper Bima Formation forms the reservoir component of this play and is sealed by the Cenomanian shales of the Gongila Formation (Figure 6.17). The Bima Formation contains known oil seepages demonstrating its reservoir potential. However, the formation consists of thin, laminated, poorly sorted sand beds with many intercalated shales in places and highly variable porosity (Omolaiye et al. 2021). This is likely to present significant challenges to storing large quantities of CO_2. The uppermost portions may show better reservoir potential (analogous to the neighboring northern Benue Trough (Bello et al. 2022, Tukur et al. 2015)) along with the earliest transgressive sands of the Gongila Formation. The Gongila Formation is composed of calcareous sandstone and thick shale deposits which may represent a regional seal (Olabode et al. 2015). The overlying shaley Fika Formation is also a regional seal. Both formations are deposited prior to the major Santonian uplift event and show significant faulting which may impact sealing quality.

The Gombe Formation: this formation is a Maastrichtian aged estuarine/ deltaic sandstone that is sealed by a regional unconformity. It is a potential reservoir in neighboring basins. However, in the Chad Basin this formation is largely absent beneath the much younger Chad Formation suggesting subaerial exposure and/or exhumation throughout the Late Cretaceous and Paleogene (Ahmed et al. 2022). In terms of sealing potential, this formation is not well documented by any geological studies and hence little is known about it's containment properties.

The Chad Formation: this formation is Pliocene aged lacustrine to alluvial sediments sealed by Chad Formation lacustrine and marine shales (Figure 6.17). It is the main source of groundwater in the Nigerian sector of the Chad Basin, proving its reservoir potential (Obaje 2009) but also raises the risk of contamination if used for CO_2 storage without significant subsurface analysis and understanding. There are three aquifers within this formation, of which the Middle Chad aquifer is the most extensive and generally lies at

Figure 6.17. General stratigraphy of the Chad Basin with potential CO_2 storage reservoir-seal pairs identified.



a depth of approximately 240-380 m, which is shallower than the expected CO_2 storage depth. The Chad Formation is mainly argillaceous suggesting it may have good sealing potential. Pliocene sediments were deposited significantly later than any major tectonic activity in the basin and few faults are mapped (Ahmed et al. 2022).

6.6.2 Pliocene Fairway Play 3a

The Pliocene-Pleistocene Chad Formation is also widely distributed across the Chad Basin (Figure 6.18a) with continental and lacustrine sandstones over 1 km thick and overlain by thick lacustrine shales (Figure 6.18b) (Moumouni et al. 2007). Wells do penetrate the central part of the basin (Figure 6.1b); however, throughout much of the basin this formation is too shallow to be considered as a potential storage reservoir (Figure 6.18c). In addition, this is the main drinking water aquifer in the area and careful investigation of the subsurface hydrological connectivity to drinking water resources would be required during site assessment. Therefore, the storage potential of this fairway area is low.

Figure 6.18a. Maximum likely preservational extent of stacked Pliocene Chad sandstone formation reservoir in the Chad Basin.

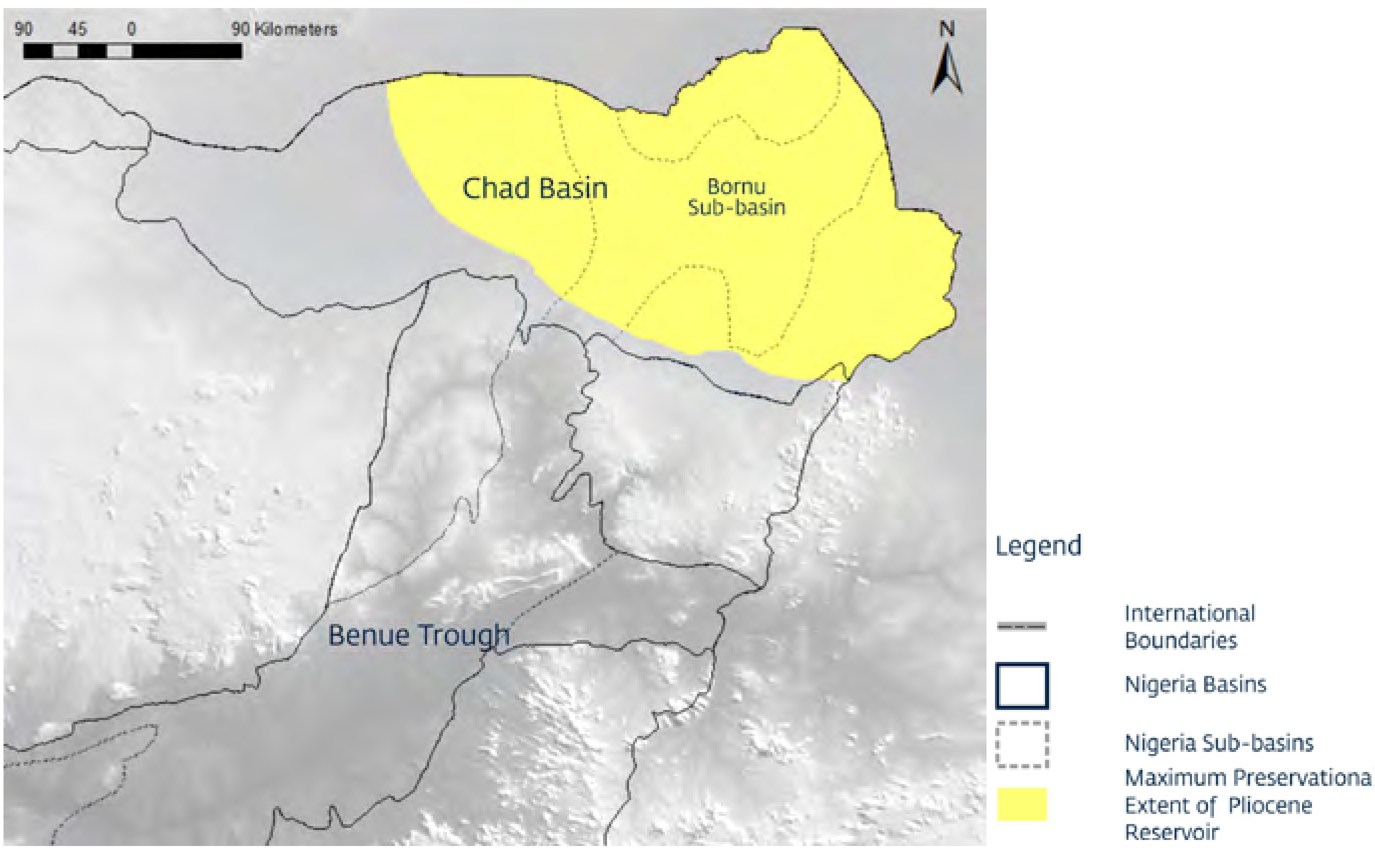


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Figure 6.18b. Maximum likely preservational extent of stacked Pliocene Chad shale formation seal in the Chad Basin.

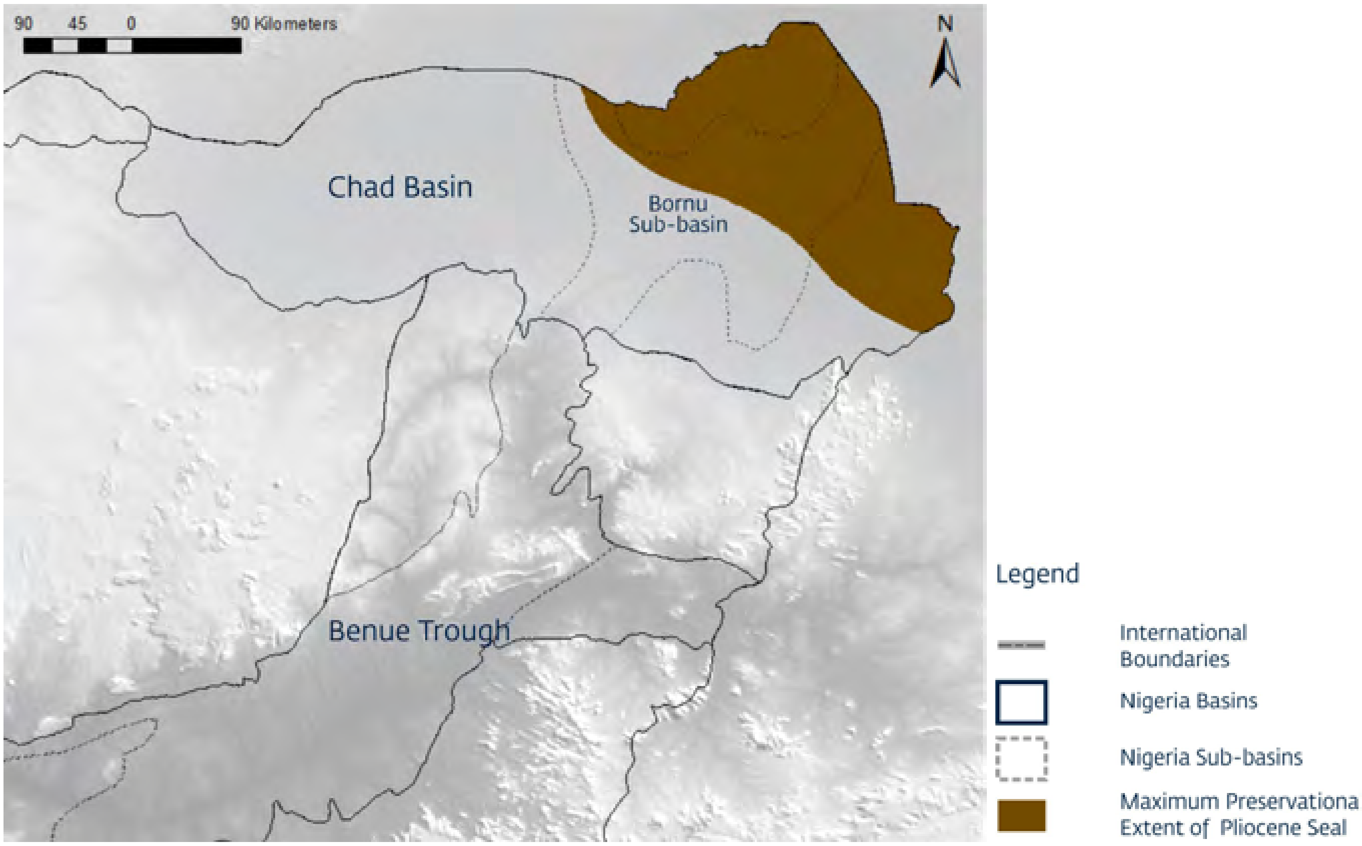

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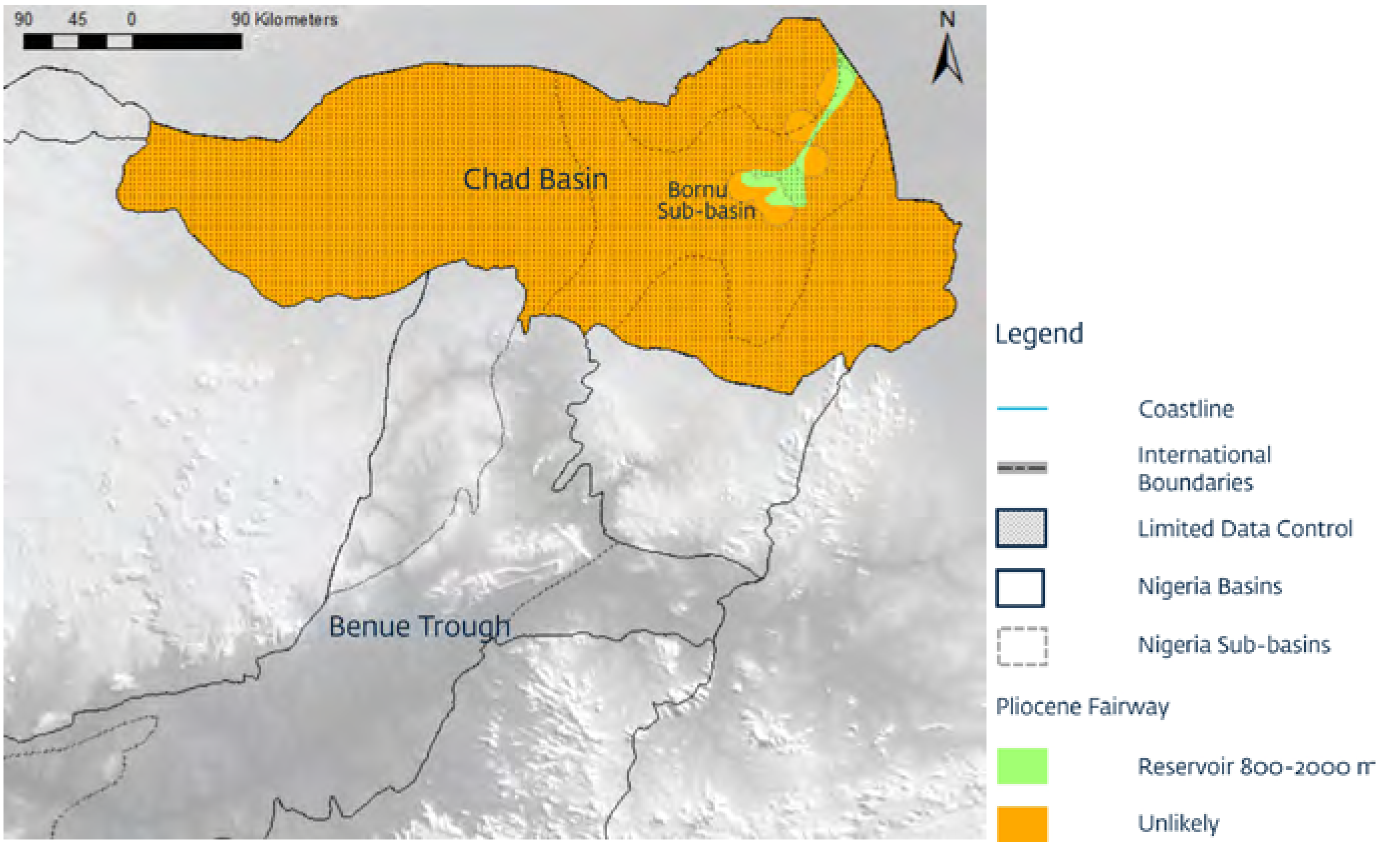
Figure 6.18c. A CCRS map illustrating the prospective fairway of the Pliocene Chad sandstone formation reservoir and Fika Shale Formation seal in the Chad Basin. The optimal reservoir depth below surface, 800-2000 m, is indicated along with the deeper 2000-3000 m interval. All other areas where the reservoir-seal pair is not present or is <800 m or >3000 m are indicated as unlikely to be suitable for storage. Areas with limited/no data control are also shown. These areas carry greater uncertainty in the play extent.



6.6.3 Cretaceous Fairway – Play 3b

As shown in Figure 6.19a, the Cretaceous continental Bima and transgressive shallow marine Gongila sandstones are expected to be widely developed across the Chad Basin. The youngest parts of the Bima Formation will likely have the best reservoir properties but be confined to rifted sub-basins and therefore have less widespread distribution. The basal sandstones of the overlying Gongila Formation were deposited during the first marine transgression into the basin and are predicted to be much more widely distributed. The upper parts of the formation are expected to be much more variable, with a transition to more open-marine mixed carbonate and shale facies representing poorer reservoir targets. The upper parts of this formation are often considered a source rock and therefore more likely to act as a seal in many areas (Olabode et al. 2015).

Sealing of the reservoir formation may be provided by the Upper Gongila Formation and/or the overlying Fika Formation, associated with a later marine transgression; this is a thick succession of shale that is widely deposited across the basin (Figure 6.19b).

The reservoir and seal formations mapped throughout much of the basin are expected to be at a suitable depth to allow for supercritical CO_2 storage (Figure 6.19c). However, the data availability to define the basin structure is low so the critical depth through the basin is uncertain.

Figure 6.19a. Maximum likely preservational extent of stacked Cretaceous Bima/ Gongila sandstone formation reservoir in the Chad Basin.

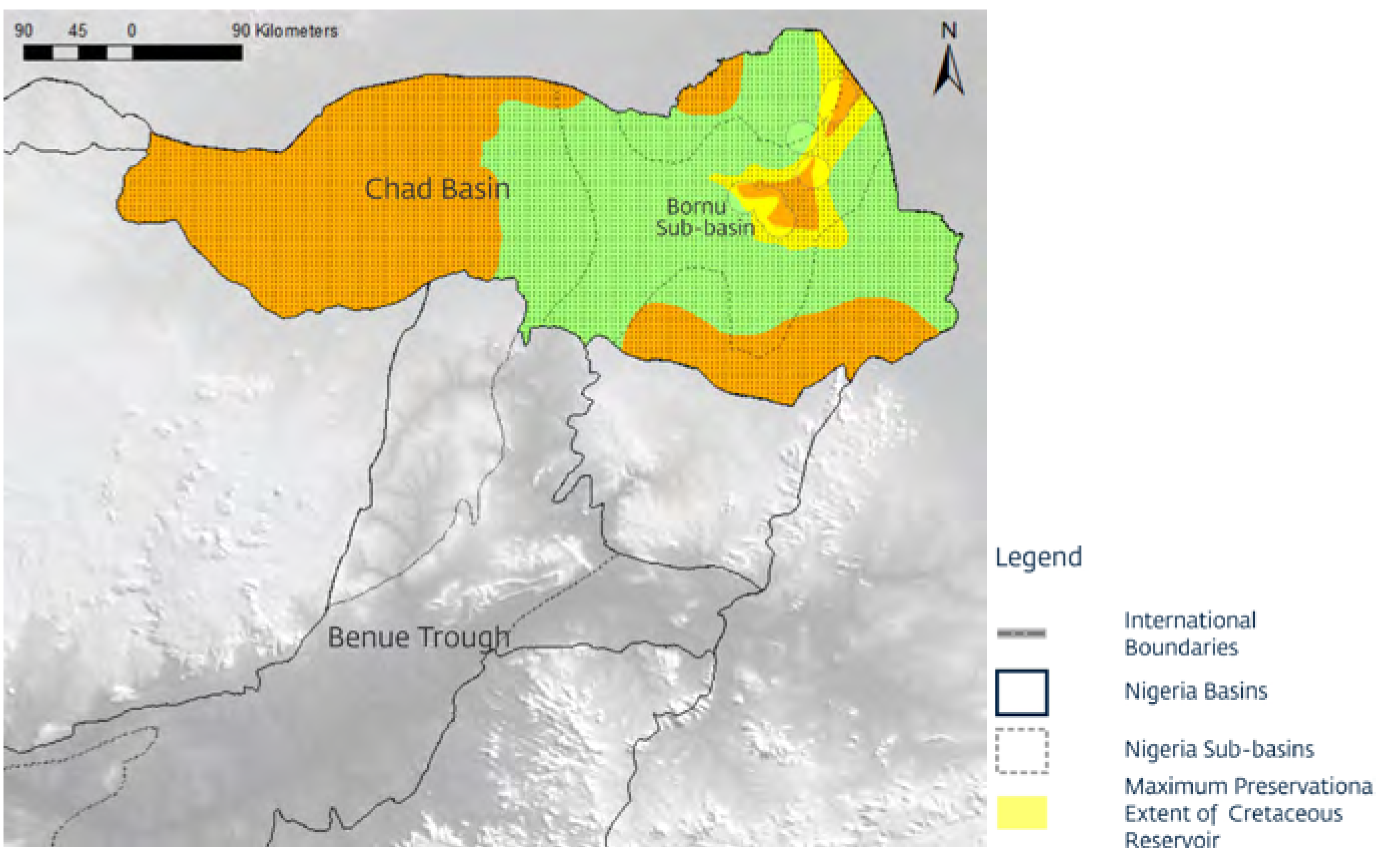


Figure 6.19b. Maximum likely preservational extent of stacked Cretaceous Fika shale formation seal in the Chad Basin.

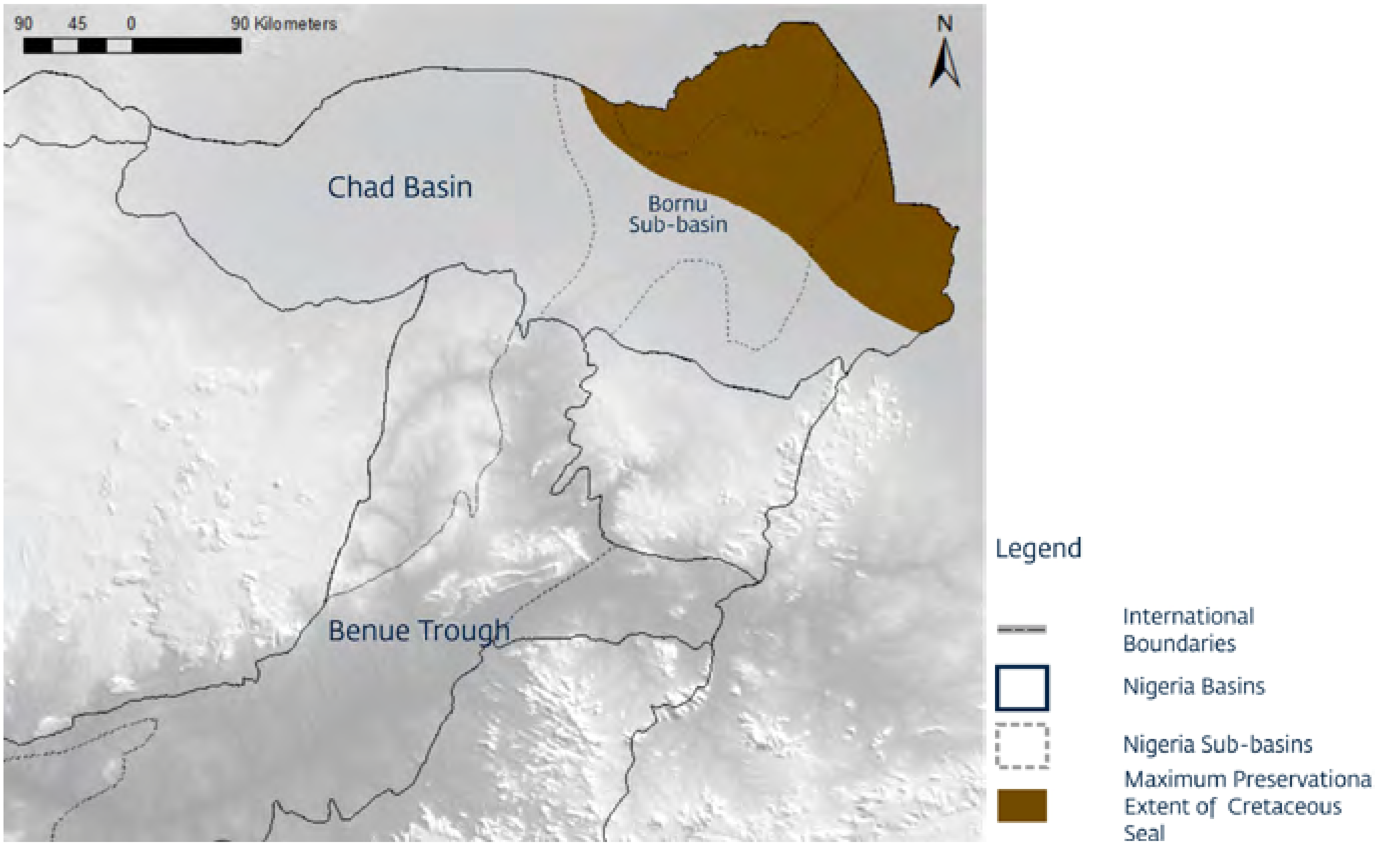
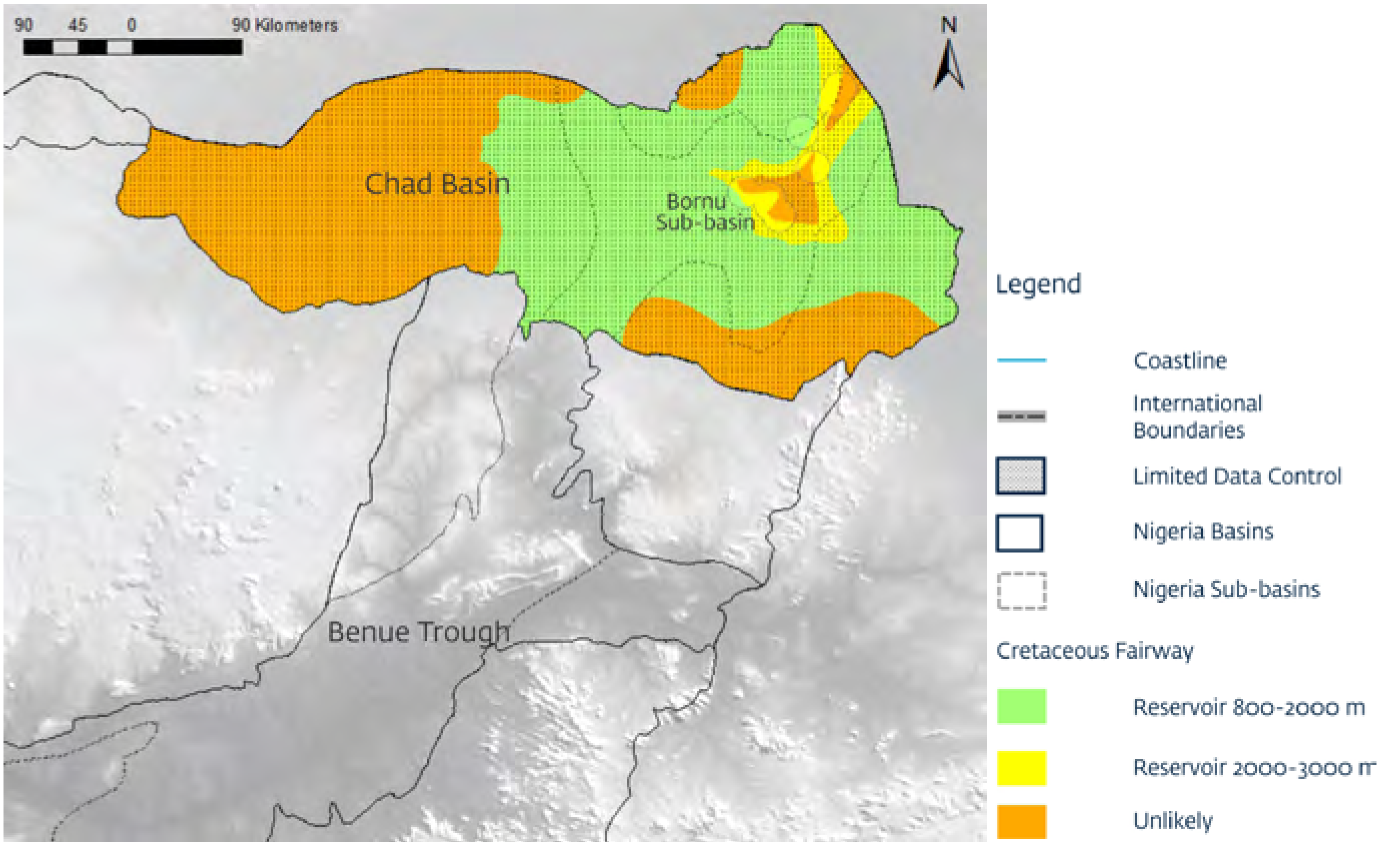


Figure 6.19c. A CCRS map illustrating the prospective fairway of the Cretaceous Bima/ Gongila sandstone formation reservoir and Gongila/ Fika Shale Formation seal in the Chad Basin. The optimal reservoir depth below surface, 800-2000 m, is indicated along with the deeper 2000-3000 m interval. All other areas where the reservoir-seal pair is not present or is <800 m or >3000 m are indicated as unlikely to be suitable for storage. Areas with limited/no data control are also shown. These areas carry greater uncertainty in the play extent.



6.6.4 Resource

Using the volumetric calculation formula described in section 5.5.3 the estimated storage capacity for the Chad Basin storage units are shown in Table 6.4.

Table 6.4. Summary of the input data and resulting prospective storage resource for the Chad Basin. Data from Olobode et al. 2015, Obaje 2009. Porosity analogue from the Benue Trough is used due to lack of data (Bello et al. 2022, Epuh and Joshua 2020, Christian et al. 2019).

Play Name	Play Age	Average Porosity (%)	Average Reservoir Thickness (m)	Net:Gross	Fairway Area (m^2)	Prospective Storage Volume (Mt)		
						Low	Medium	High
Chad	Pliocene	32	400	0.3	2,022	27,700	108,700	293,500
Bima/ Gongila	Cretaceous	18	150	0.8	7,978	62,000	241,000	651,000

Source: Halliburton

6.6.5 Geo-risk and SRMS

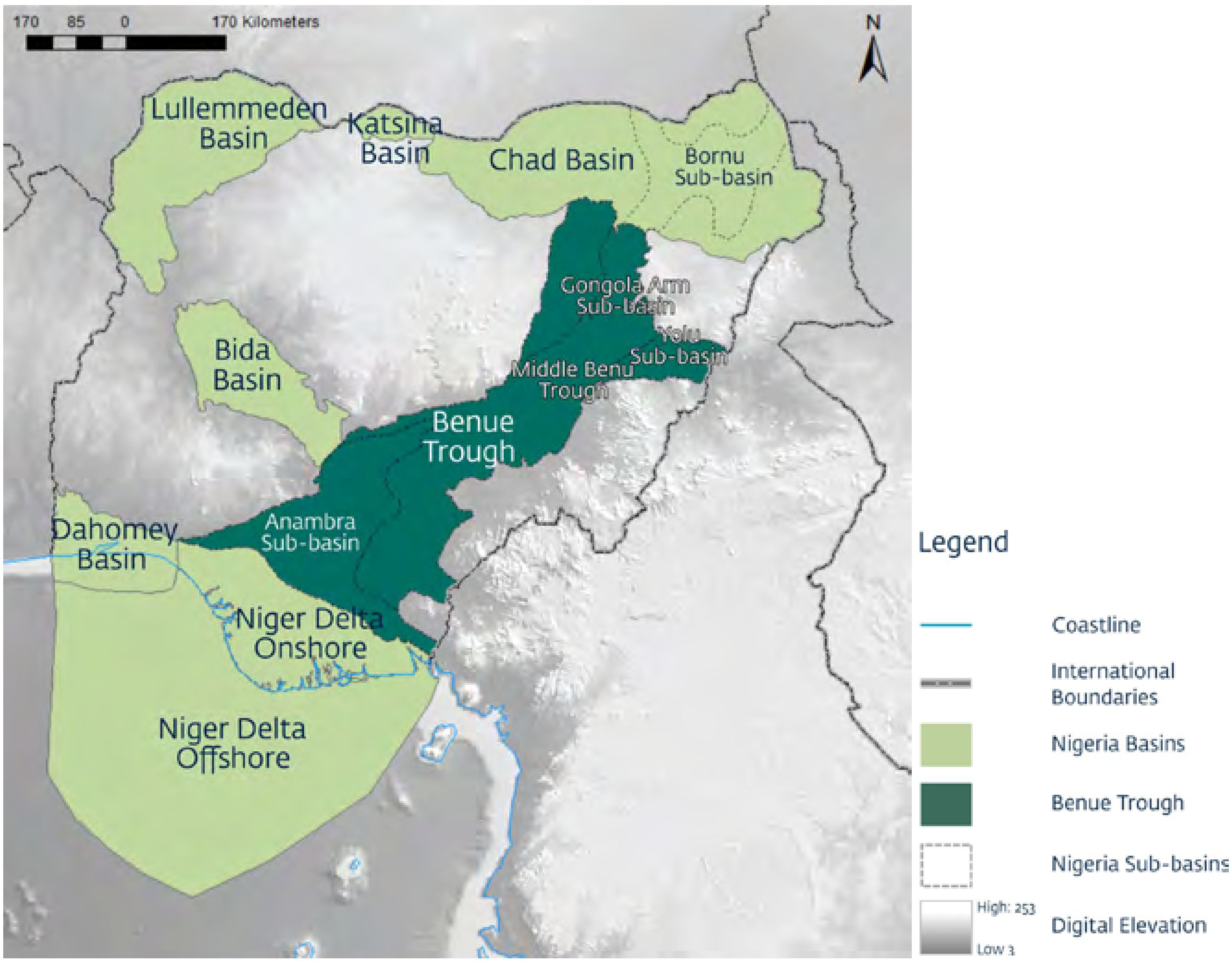
The geo-risk criteria outlined in section 5.4.4 indicate that the Chad Basin carries a risk of 24 for the Pliocene storage play, 28 for the Gombe Santonian-Maastrichtian play and 33 for the Albian-Santonian Bima/ Gonglia play.

The SRMS Classification using the decision-based flow chart outlined in section 5.3, gives the Chad Basin a classification of an Undiscovered, Prospective Sequence Play. Although there is the presence of wells in the eastern sector of the basin (Figure 6.1b), it is not known if they penetrate the potential storage formations and as such this area will remain as an Undiscovered classification. The Cretaceous formations in eastern area are likely to be unsuitable for CO_2 storage due to reservoir depths being too great (Figure 6.19c).

6.7 Benue Trough Play 4

The Benue Trough (Figure 6.20) is a frontier basin with moderate data coverage. Cretaceous plays in the Benue Trough are within the CO_2 storage depth window. Drilling has been focused in the northern and southern branches of the basin, but not in the Middle Benue Trough (Turkur et al. 2015), leaving this part of the basin with very low data coverage. The basin sits in the Yobe, Gombe, Adamawa, Plateau, Taraba, Nassarawa, Benue, Kogi, Edo, Delta, Anambra, Enugu, Ebonyi, Cross River, Imo, Abia, Akwa Ibom, and Ondo states.

Figure 6.20. Location of the Benue Trough



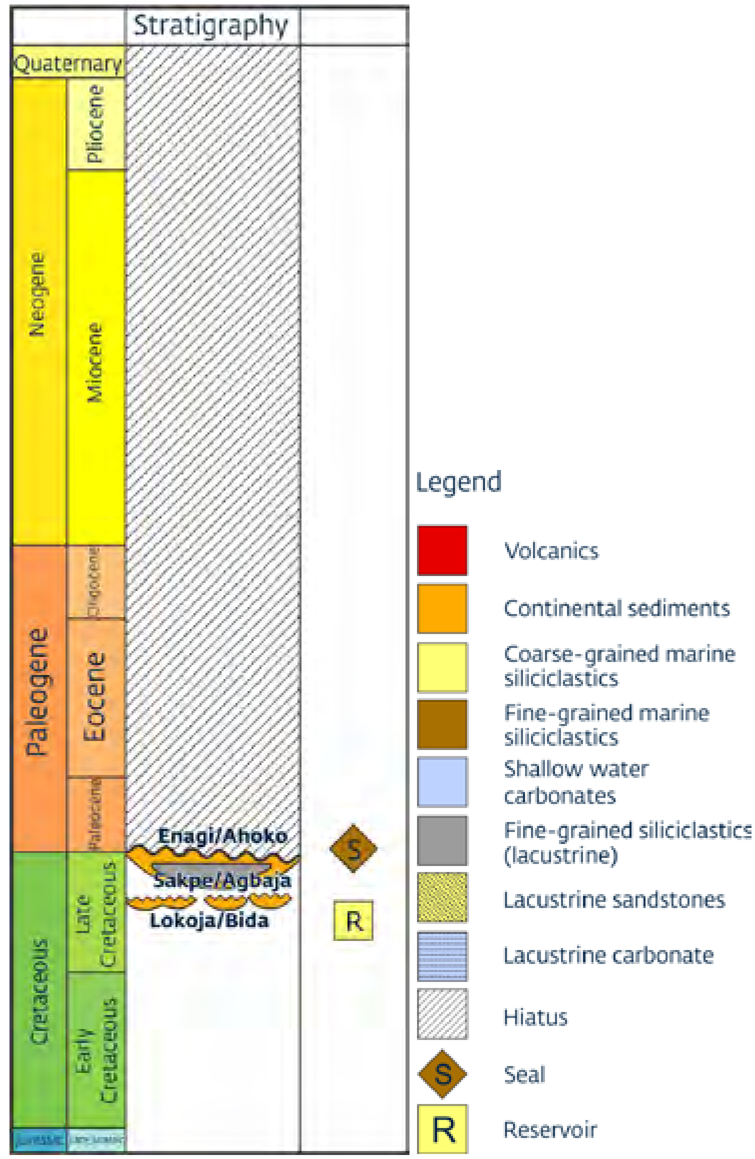
Source: Halliburton

6.7.1 Potential Reservoir-Seal pairs

Lithostratigraphic nomenclature varies from the north to the south of the basin, however the stratigraphy for all reservoir and seal pairs (Figure 6.21) can be correlated across the sub-basins.

Bima/ Pindiga or Asu River Group: the Albian age continental Bima/ Yolde (Northern Benue Trough) or Mamfe Formation (Southern Benue Trough) sandstones are sealed by marine shales of the Pindiga Formation (Northern Benue Trough) or Abakaliki Formation (Southern Benue Trough). In the northern basin these have heavy diagenetic alteration affecting their porosity (Bello et al. 2022). The Cenomanian Yolde Formation is an important aquifer in the Upper Benue Trough (Abubaker 2014). The Asu River Group is predominantly shale (Obasi and Selemo 2018) and may act as a regional seal in the Southern Benue Trough (Lar et al. 2023). In the Northern Benue Trough, the lowest part of the Pindiga Formation is a carbonate which places uncertainty on its sealing potential due to mechanical response (for example brittle deformation or fracturing) and geochemical sensitivity (Goro et al. 2019). After the deposition of these formations, a major uplift occurred creating significant faulting and tight folding (Abubaker 2014, Obasi and Selemo 2018).

Figure 6.21. General stratigraphy of the Benue Trough with potential CO_2 storage reservoir-seal pairs identified.



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Pindiga/ Gongila or Eze Aku Group: the Turonian age marine sandstones of the Pindiga Formation (Northern Benue Trough) or Amasiri Formation (Southern Benue Trough) forms a reservoir-seal pair with the Turonian – Coniacian marine shales of the Gongila/ Fika Formations (Northern Benue Trough) or Awgu Formation (Southern Benue Trough). Sandstones of the Amasiri Formation in the Southern Benue Trough show moderate sorting with calcite cement and have high enough porosity and permeability to form a potential reservoir formation (Obasi and Selemo 2018). The equivalent Pindiga Formation in the Northern Benue Trough also serves as an aquifer in the Kumo area (Abubaker 2014). The sands and thick, regional shales of the Gongila/ Fika Formation could form good plays for CO_2 storage (Goro et al. 2019). In the southern Benue Trough sealing may be provided by the Coniacian Awgu Formation (Obasi and Selemo 2018). As with the older plays, intense faulting and folding is expected within these formations and may affect storage resource and seal efficiency.

Gombe or Mamu/ Nsukka: the Maastrichtian continental sandstones of the Gombe Formation (Northern Benue Trough) or Mamu/ Nsukka Formations (Southern Benue Trough) form a reservoir-seal pair where sealed by a regional unconformity/ intercalated shale. The continental-deltaic Gombe Formation is likely to have highly variable porosity and permeability (Abubaker and Ahmadov 2022). Intercalated shales are recorded and may provide some sealing capacity to the Gombe Formation, but may not be competent or laterally extensive, downgrading this as a potential CO_2 storage play (Abubaker 2014, Obasi and Selemo 2018). Post-Santonian sediments have not suffered any pronounced deformation, due to little or no tectonism (Nwaiide 2022).

Cenozoic formations are generally not buried sufficiently deep to be considered potential CO_2 storage plays within the basin and therefore not assessed.

6.7.2 Cretaceous Fairway

The continental/ fluvial sandstones of the Bima Formation and overlying transgressive shallow marine Yolde sandstones are extensively deposited across the Benue Trough (Figure 6.22a). The uppermost Bima Formation sands are likely to have the best porosity (Bello et al. 2022, Turkur et al. 2015) and further high-resolution mapping of their distribution would help to better define the reservoir area.

There are several shaley formations which could represent viable sealing units for the Bima/ Yolde sandstones (Figure 6.22b). These are expected to be widely distributed across the basin. However, as with the Chad basin, there is a high degree of uncertainty on their distribution due to limited data availability, so significant extra data collection would be required to better assess seal thickness and integrity.

Much of the Albian-Coniacian Bida/ Yolde target reservoir interval in the Benue Trough is at a good depth for supercritical CO_2 storage (Figure 6.22c); however, data are focused in a few key areas and further data generation activities will be required to properly define fairway extent away from these. Overall, there is a large potential fairway for CO_2 storage (Table 6.5) and this basin may merit further investigation due to close proximity to CO_2 sources (Figure 6.22d).

Figure 6.22a. Maximum likely preservational extent of stacked Cretaceous Bima/ Yolde Formation sandstone reservoir in the Benue Trough.

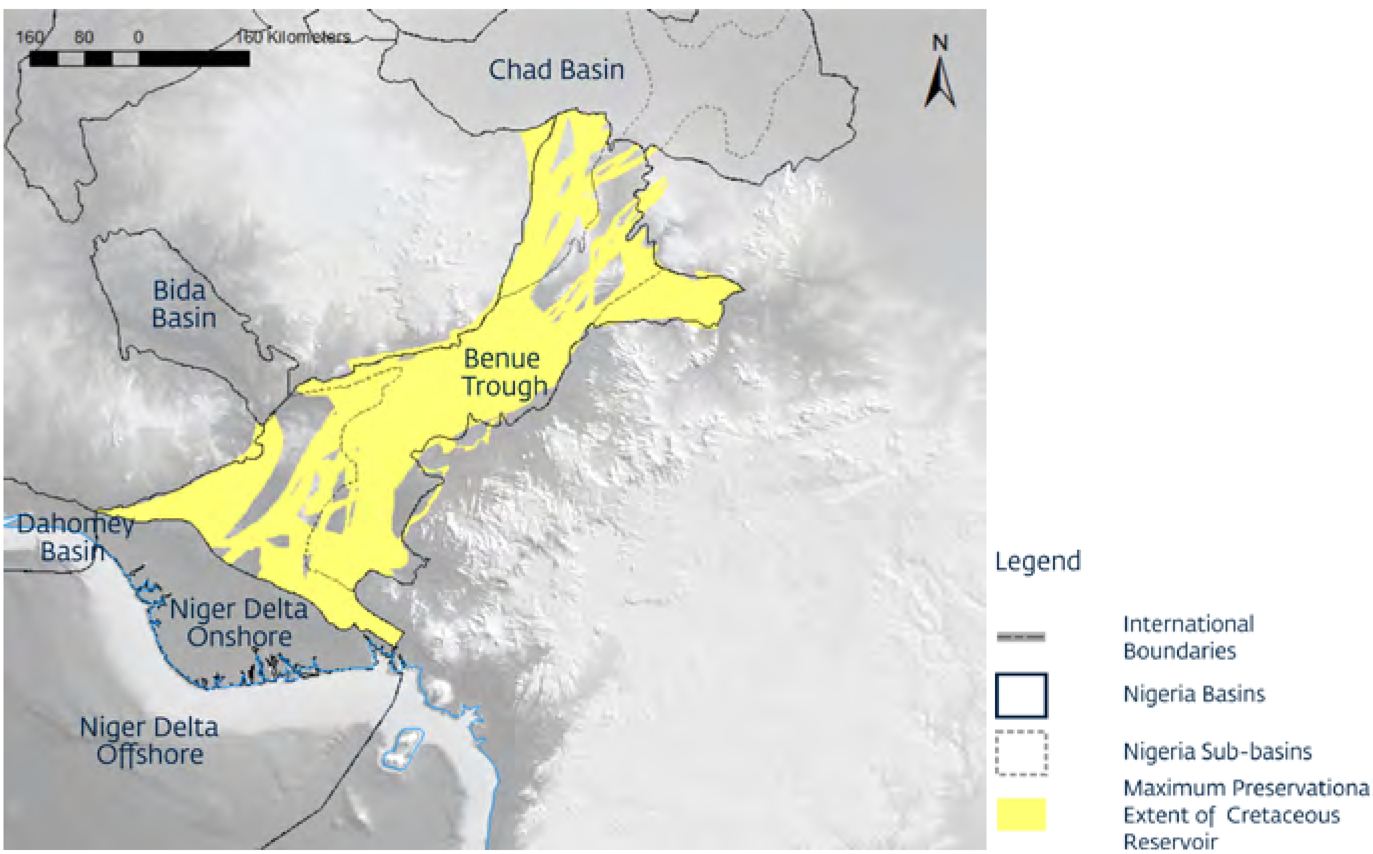

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Figure 6.22b. Maximum likely preservational extent of stacked Cretaceous Bima/ Yolde Formation shale seal in the Benue Trough.

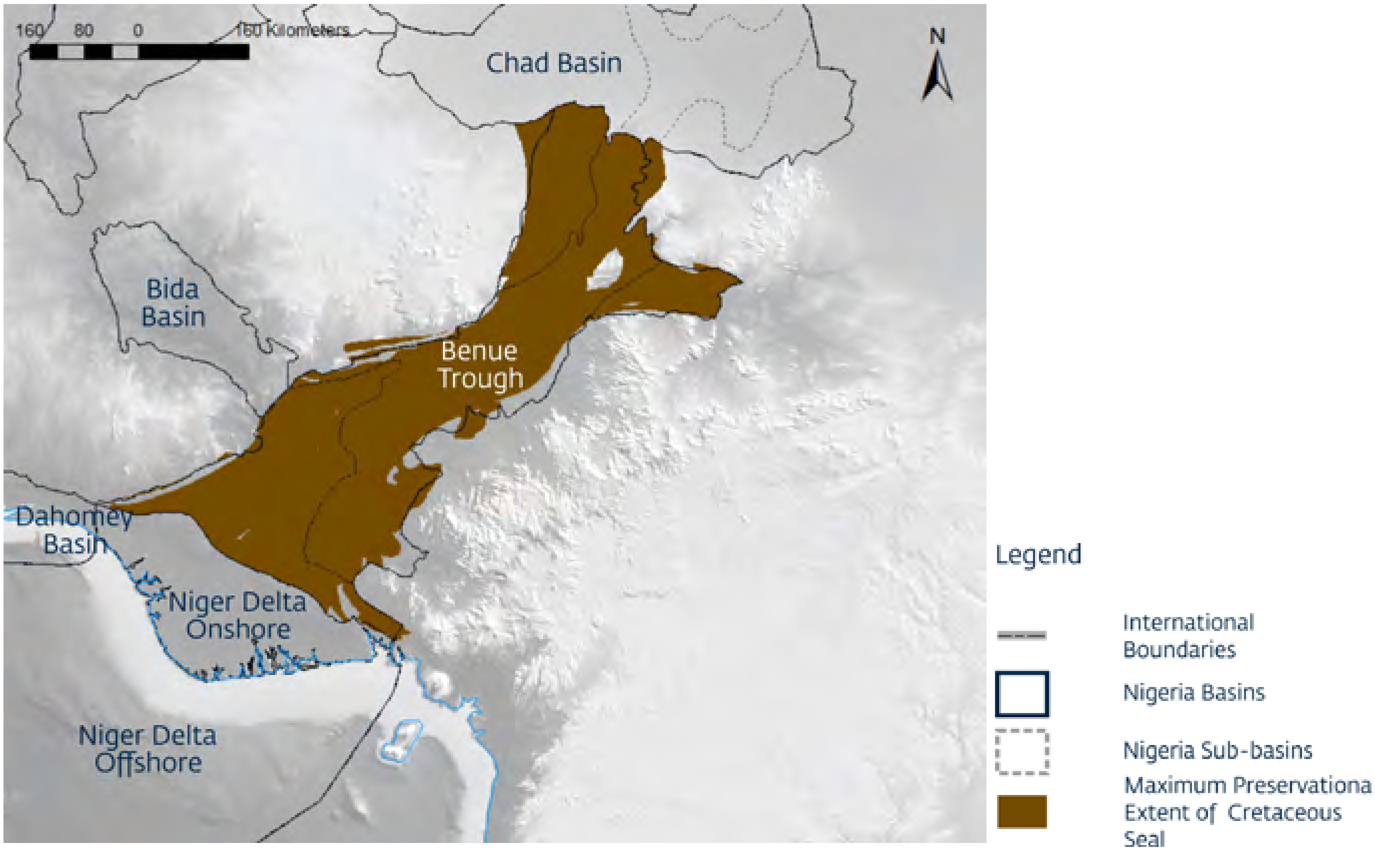


Figure 6.22c. Map illustrating the prospective fairway of the Cretaceous sandstone Bima/ Yolde Formation in the Benue Trough. The optimal reservoir depth below surface, 800-2000 m, is indicated along with the deeper 2000-3000 m interval. All other areas where the reservoir-seal pair is not present or is <800 m or >3000 m is indicated as unlikely to be suitable for storage. Areas with limited/no data control are also shown. These areas carry greater uncertainty in the play extent.

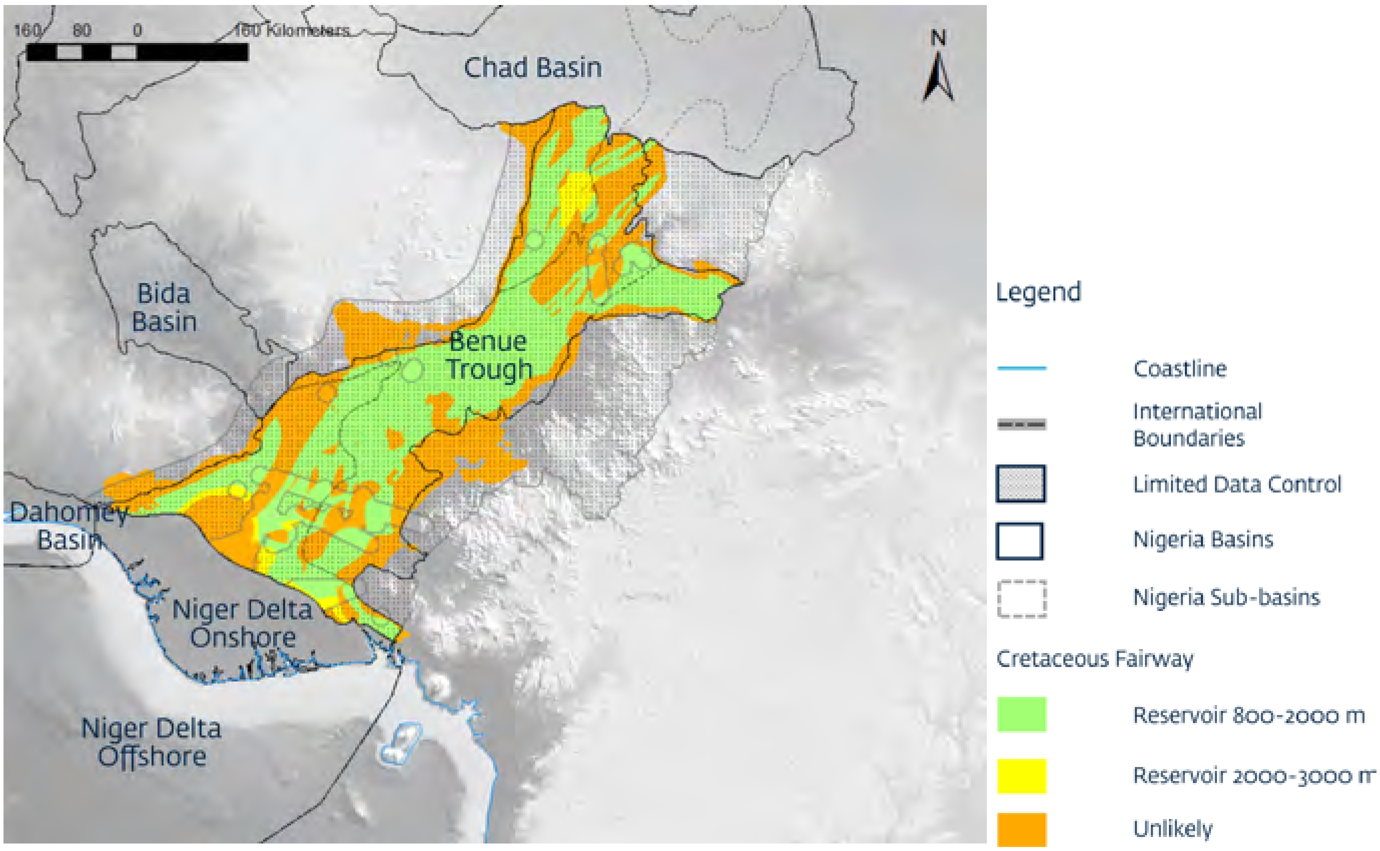
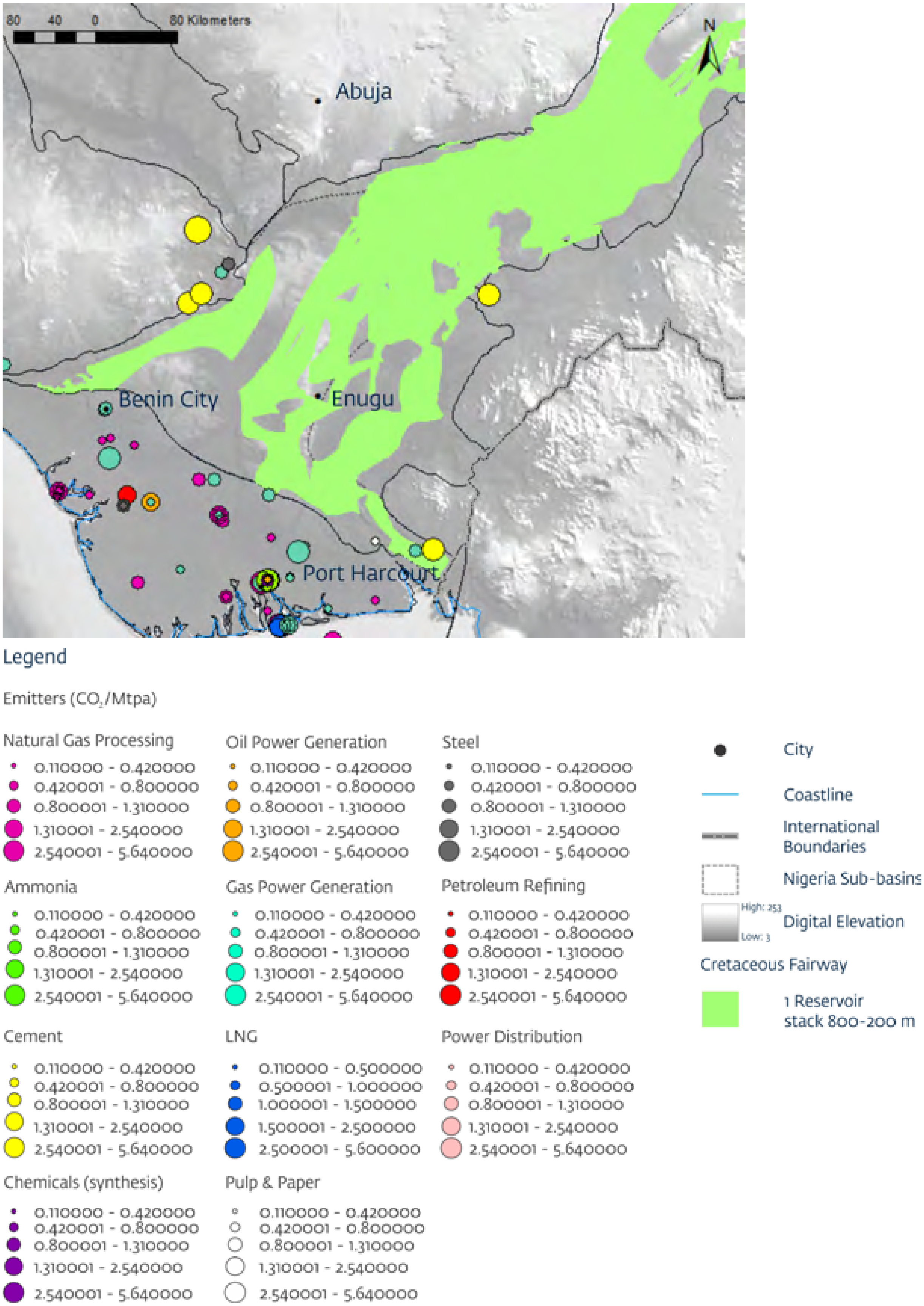


Figure 6.22d. Map of Cretaceous fairway in the Benue Trough (delineated in green) with local CO_2 emitters.



Source: Halliburton, BCG

6.7.3 Resource

Using the volumetric calculation formula described in section 5.5.3 the estimated storage capacity for the Benue Trough storage units are shown in Table 6.5.

Table 6.5. Summary of the input data and resulting prospective storage resource for the Benue Trough. Data from Obasi and Selemo 2018, Okoro et al. 2016. NB formation properties likely to vary north to south. Net-to-gross value analogue is from the Niger Delta.

Play Name	Play Age	Average Porosity (%)	Average Reservoir Thickness (m)	Net:Gross	Fairway Area (m^2)	Prospective Storage Volume (Mt)		
						Low	Medium	High
Amasiri or Pindiga/ Gongila	Turonian - Coniacian	11	100	0.7	106,214	295,000	1,157,000	3,125,000

Source: Halliburton

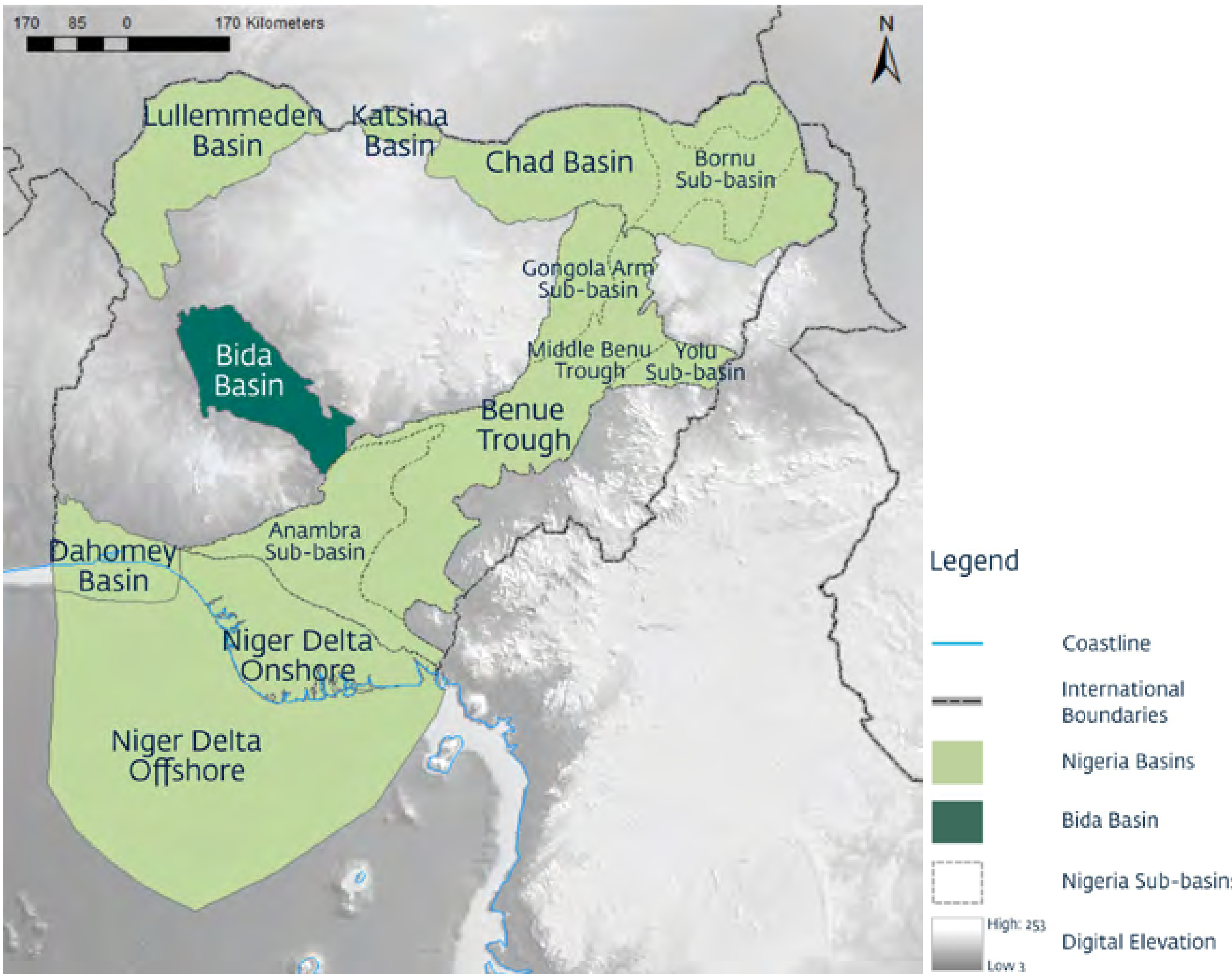
6.7.4 Geo-risk and SRMS Classification

The geo-risk criteria outlined in section 5.4.4 indicate that the Benue Trough carries a risk index of 25 for the Cenozoic Kerri-Kerri storage play, 25 for the Gombe Santonian-Maastrichtian play, 28 for the Turonian- Santonian Pindiga/ Fika play, 28 for the Albian- Cenomanian Yolde/ Bima play, and 33 for the Albian-Santonian Bima/ Gonglia play. The SRMS classification used by the decision-based flow chart outlined in section 5.3 gives the Benue Trough a classification of Undiscovered, Prospective Sequence Play for the majority of the basin due to the very limited and/or absence of wells (Figure 6.1b).

6.8 Bida Basin – Play 5

The Bida Basin (Figure 6.23) is a frontier basin with poor data coverage and no exploration wells drilled as of 2018 (Figure 6.1b). As a result, there is a high degree of uncertainty as to whether good quality reservoirs, traps and seals are present for potential CO_2 storage. Cretaceous plays may be within the CO_2 storage depth window, with sediments at the basin center up to 4700 m thick, decreasing from the central portion to the flanks of the basin (Obaje et al. 2011). The basin sits in the Niger, Federal Capital Territory, Kwara and Kogi states.

Figure 6.23. Location of the Bida Basin



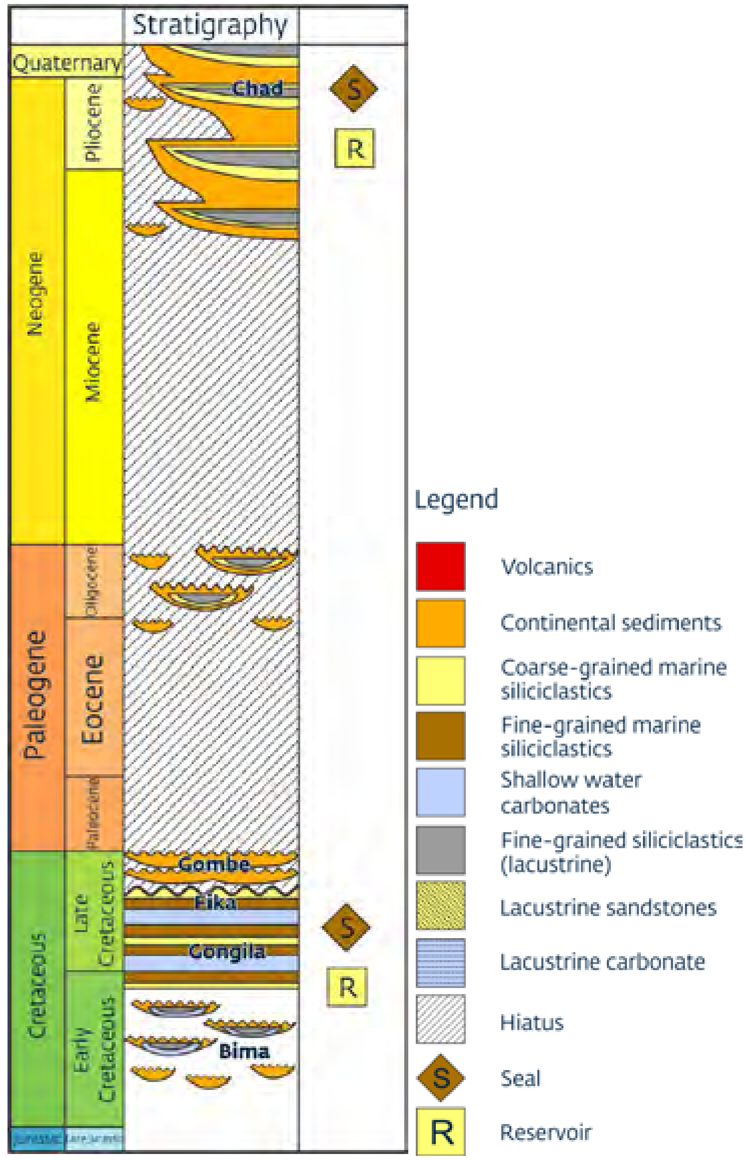
Source: Halliburton

6.8.1 Potential Reservoir-Seal Pairs

There is one potential reservoir-seal pair for CO_2 storage within the basin (Figure 6.24).

Bida/ Enagi or Lokoja/ Patti: the Santonian – Campanian age lacustrine/ continental sandstone of the Bida or Lokoja Formation form a reservoir-seal pair with the Campanian – Maastrichtian Enagi or Patti Formation lacustrine shales. The Lokoja Formation has properties that suggest good reservoir potential (Aigbadon et al. 2023) and is an aquifer within the basin. The Patti and Agbaja Formations may form regional seals within the basin (Obaje et al. 2011). Sediments were deposited after the major regional Santonian tectonic event, which could result in less intense faulting of these sediments (Obaje et al. 2020).

Figure 6.24. General stratigraphy of the Bida Basin with potential CO_2 storage reservoir seal pairs identified.



6.8.2 Cretaceous Fairway - Play 5

The Bida Basin is the least well understood basin in this study with no well data available (Figure 6.1b) to assist the mapping exercise. Both reservoir and seal are mapped as covering much of the basin based on the understanding of the regional geology in the area(Figure 6.25a,b). However, facies may be more variable within the basin and significant further work is required to confidently define the sedimentology and structure in this area. Much of the basin is expected to be at a suitable depth for CO_2 storage (Figure 6.25c). Overall, the potential storage volume in this basin could be high (Table 6.5) and this basin may merit further investigation due to close proximity to CO_2 sources (Figure 6.25d).

Figure 6.25a. Maximum likely preservational extent of stacked Late Cretaceous Lokoja/Bida Formation sandstone reservoir in the Benue Trough.

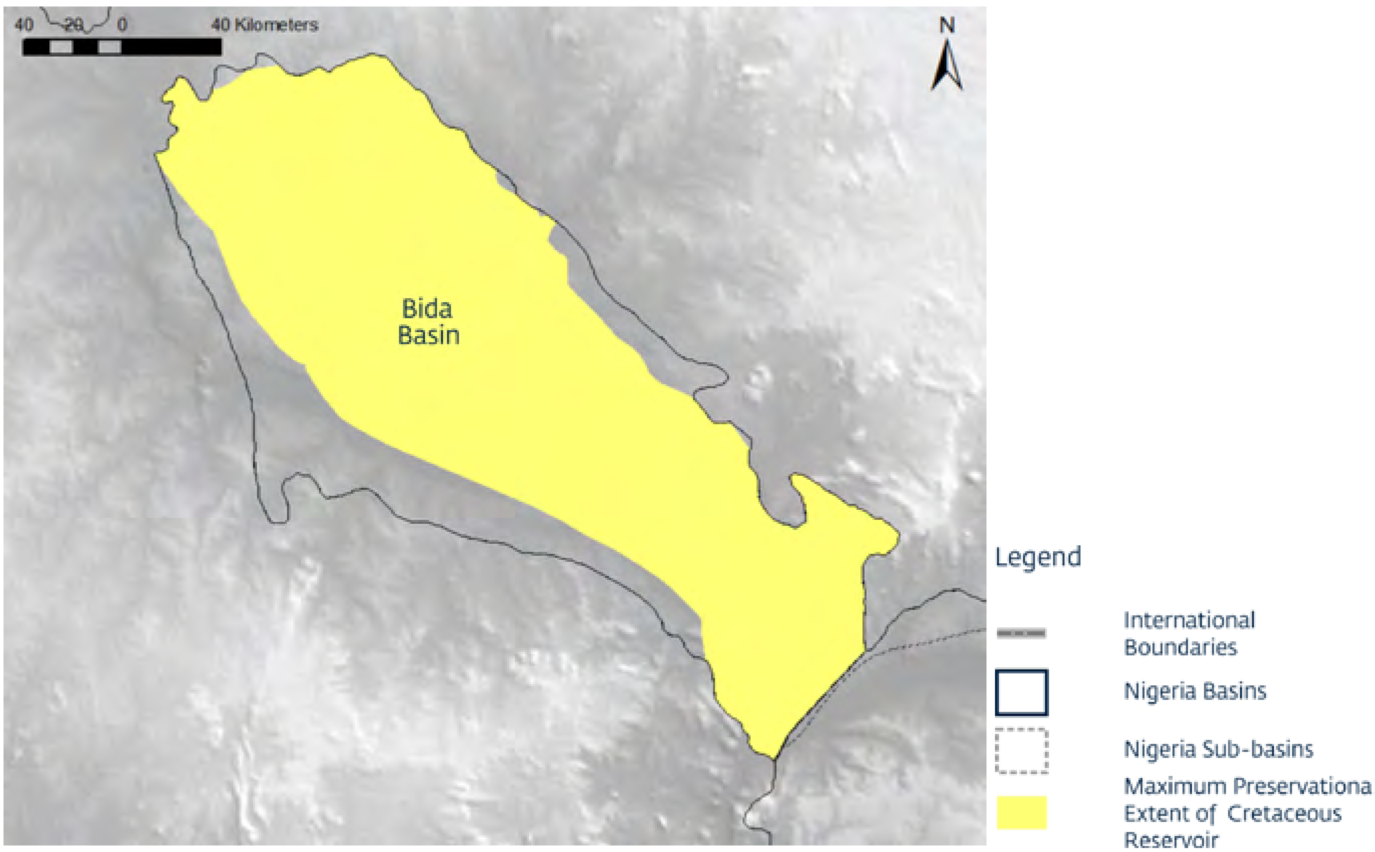


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Figure 6.25b. Maximum likely preservational extent of stacked Late Cretaceous Lokoja/ Bida Formation shale seal in the Benue Trough.

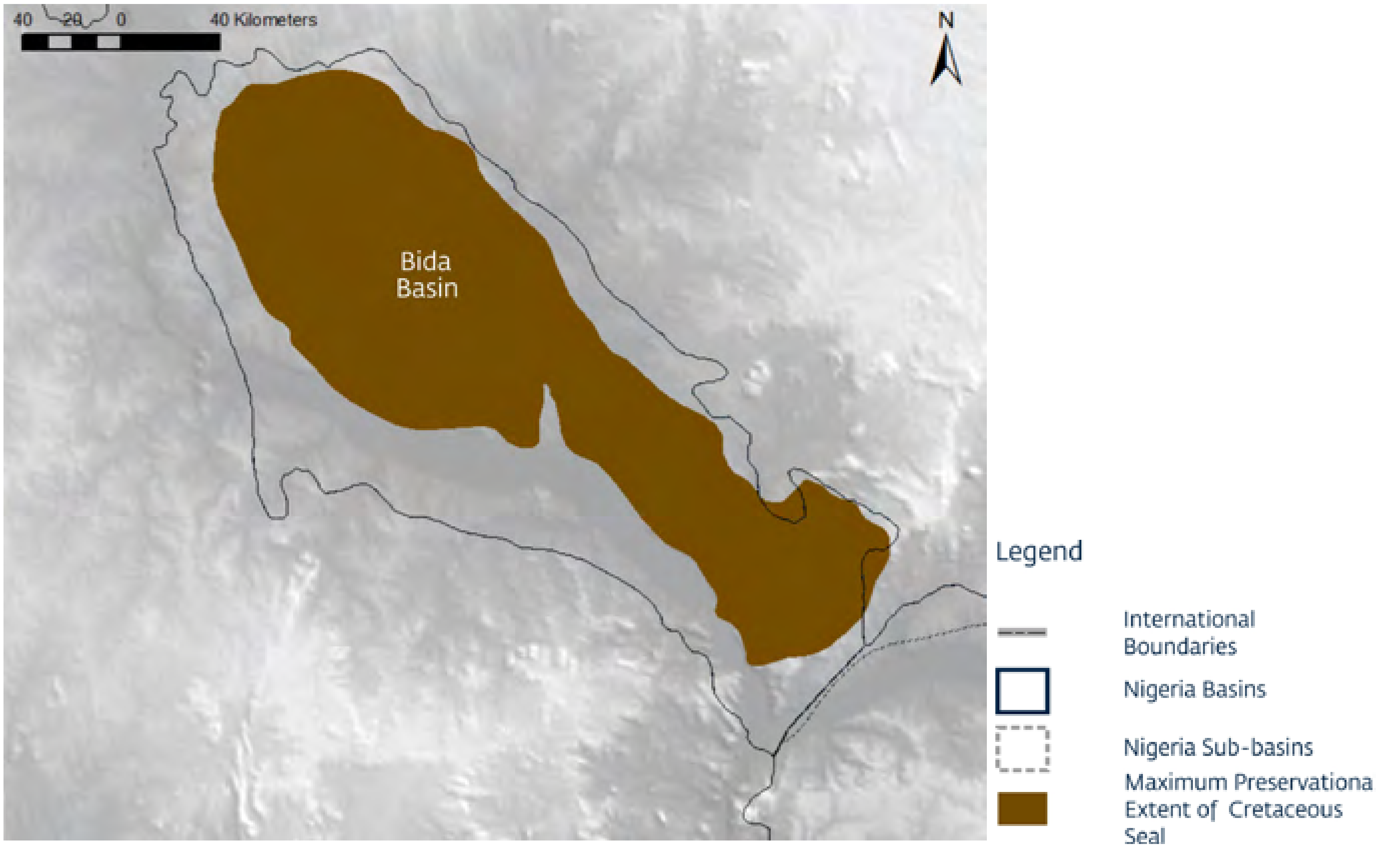


Figure 6.25c. Map illustrating the prospective fairway of the Late Cretaceous Lokoja/ Bida Formation reservoir and shale seals in the Benue Trough. The optimal reservoir depth below surface, 800-2000 m, is indicated along with the deeper 2000-3000 m interval. All other areas where the reservoir-seal pair is not present or is <800 m or >3000 m is indicated as unlikely to be suitable for storage. Areas with limited/no data control are also shown. These areas carry greater uncertainty in the play extent.

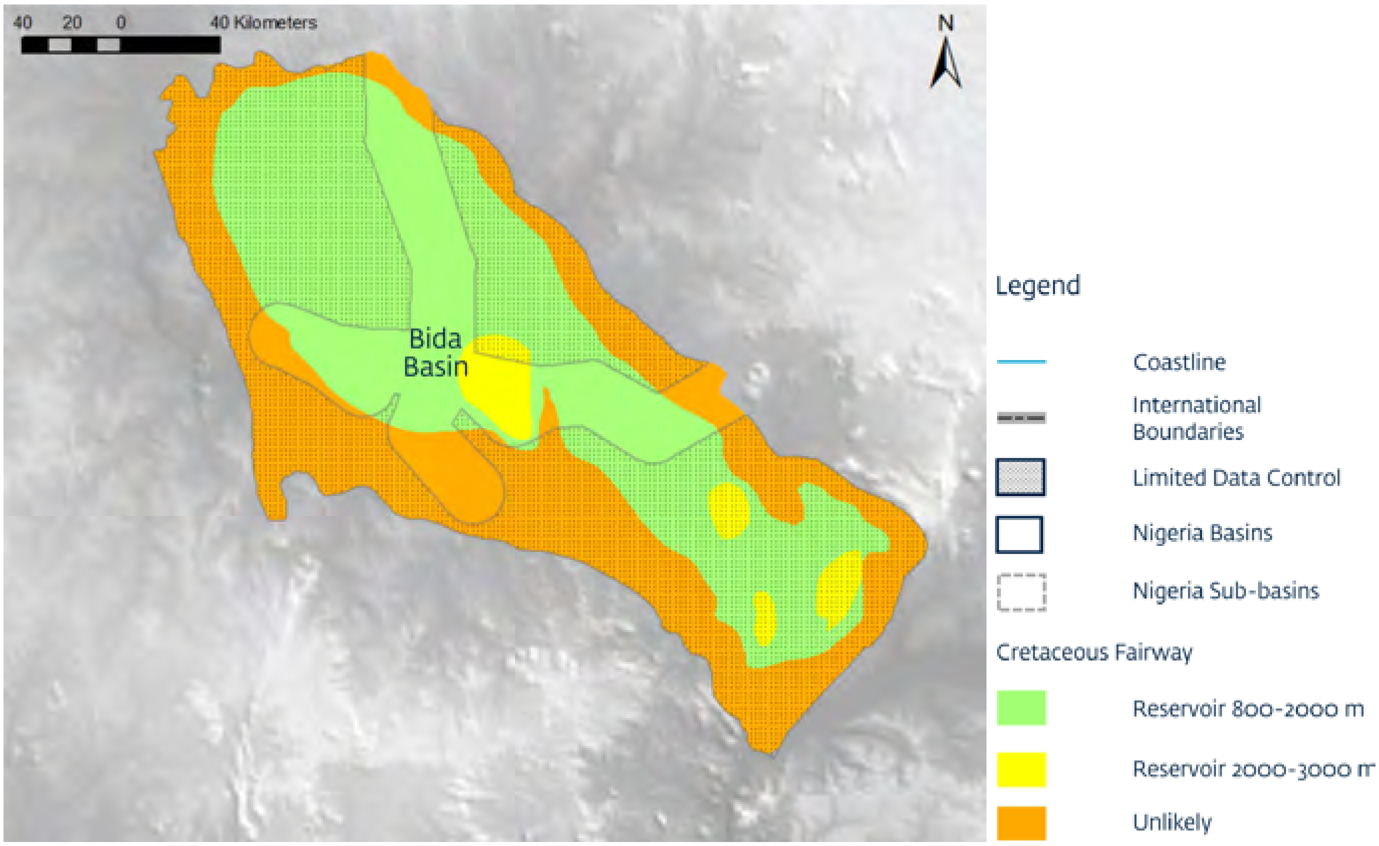
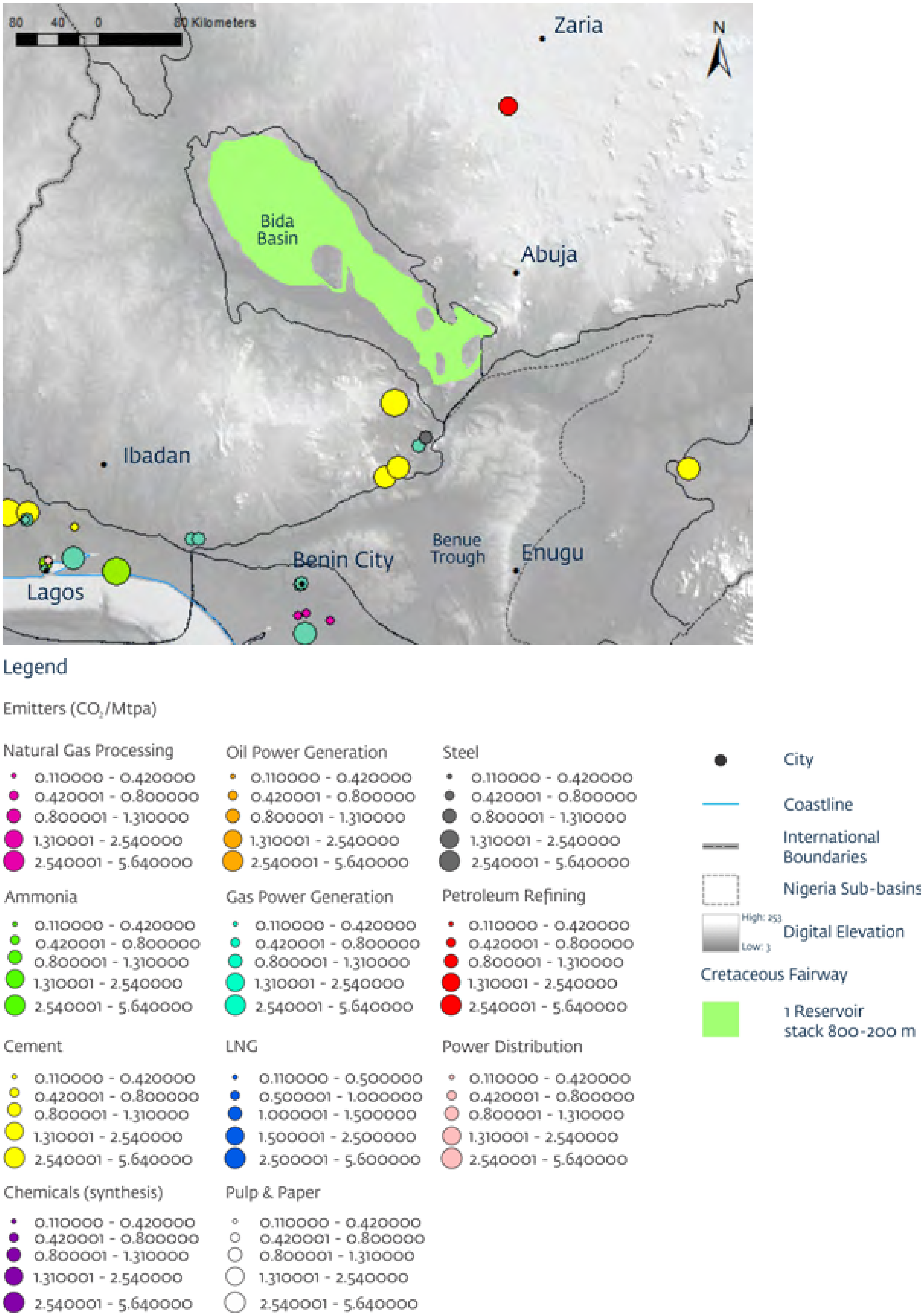


Figure 6.25d. Map of the Cretaceous fairway in the Bida Basin (delineated in green) with local CO_2 sources.



Source: Halliburton, BCG

6.8.3 Resource

Using the volumetric calculation formula described in section 5.5.3 the estimated storage resource for the Bida Basin storage units are shown in Table 6.6.

Table 6.6. Summary of the input data and resulting prospective storage resource for the Bida Basin. Data from Aigbadon et al. 2023.

Play Name	Play Age	Average Porosity (%)	Average Reservoir Thickness (m)	Net:Gross	Fairway Area (m^2)	Prospective Storage Volume (Mt)		
						Low	Medium	High
Lokoja/ Sakpe or Patti/ Enagi	Late Cretaceous	30	213	0.7	20,976	335,000	1,314,000	3,547,000

Source: Halliburton

6.8.4 Geo-Risk and SRMS Classification

The geo-risk criteria outlined in section 5.4.4 indicate that the Bida Basin carries a risk index of 42 for the Cretaceous play. The SRMS classification used by the decision-based flow chart outlined in section 5.3 gives the Bida Basin one of the lowest classifications in Nigeria due to the very limited data on the reservoir. It has a classification of Undiscovered Basin Play.

6.9 Depleted Hydrocarbon Fields

A key finding from the screening for CO_2 plays in Nigeria is that the Niger Delta carries the most optimal storage, with the Miocene formations of the Niger Delta having the greatest potential. Depleted oil and gas fields and near-depleted oil and gas fields in this basin (Figure 6.26) could be high-graded for CO_2 storage. The prominence of data, the well characterized fields that provide identified prospects, a dynamically understood subsurface and the proven ability to store gases long-term are key contributing arguments for this. Near-depleted oil and gas fields are those that have produced at least 70% of their ultimate recovery potential.

Capacity to store reasonable volumes of captured CO_2 is a critical requirement for oil and gas fields to be considered as viable storage candidates. A CO_2 resource estimation and location for individual depleted and near-depleted fields in Nigeria is shown in Figures 6.27a-d with a minimum resource (low) case of 10 Mt. Some fields are not shown due to very low-resource estimates (<10 Mt), which are generally not commercially viable unless considered as part of a cluster project. The methodology used to calculate resource is based on hydrocarbon replacement volume. The Niger Delta's oil and gas fields contain reservoirs with sufficient porosity and permeability to store the fluids. Therefore, the calculation's approach is that the free space (voidage) created in the reservoir as a result of oil and gas production that is now available for CO_2 storage. This assumption does not take aquifer drive into account. Aquifer ingress may reduce reservoir voidage available for CO_2 storage. This resource calculation is lower than the high-level total resource estimate generated in the play approach (Section 6.4-6.8) which considers the total gross storage resource of an entire formation at an expected sweep efficiency for a set lithology type. The hydrocarbon field CO_2 storage estimation was carried out with a deterministic approach. This means that single values were used from the range of values for each parameter of the CO_2 storage calculation. This deterministic estimation is shown for low, mid, and high values of each parameter to arrive at respective low, mid, and high values of CO_2 storage for each field.

A summary of the key takeaways for Nigeria's oil and gas fields are as follows:

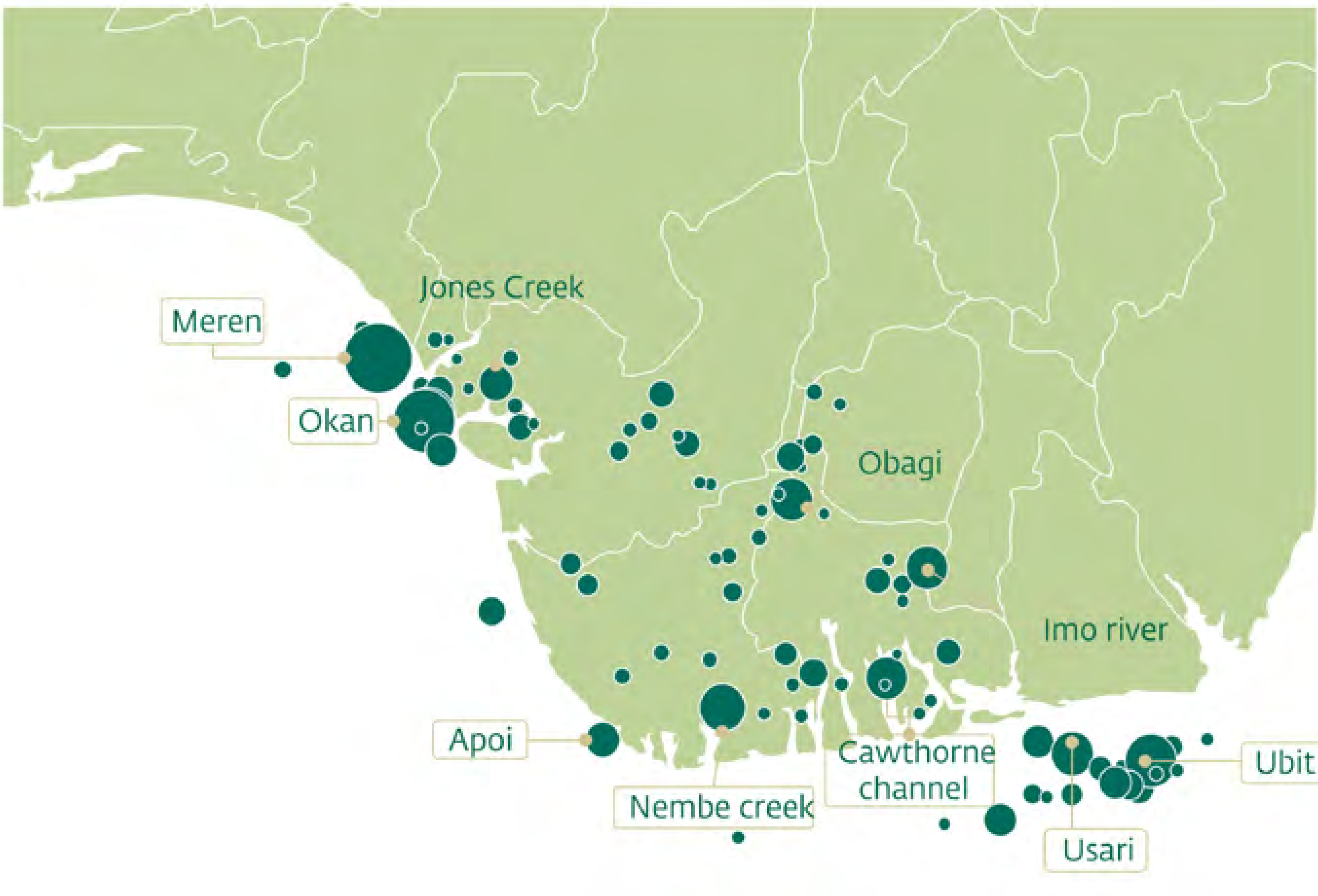
1. Around half of the CO_2 storage capacity in depleted and near-depleted oil and gas fields is situated onshore Niger Delta as seen in Figure 6.26. The underlying reason for this is that production in the onshore area of the Niger Delta commenced in late 1950s with the Oloibiri field, making this most mature terrain of the basin. For similar reasons, the onshore area also holds the largest proportion of abandoned fields.

2. The study estimates that 41% of CO_2 resource capacity in depleted and near-depleted oil and gas fields of the Niger Delta are within shallow offshore terrain (i.e., less than 150 m water depth). Shallow offshore production commenced in early 1970s with the Okan field, hence this terrain is also quite mature.

3. In deeper waters (i.e. greater than 150 m water depth), there is much less CO_2 storage resource identified because the fields in this terrain have produced less of their potential volume, therefore, there are few depleted and near-depleted fields.

4. In terms of quantity, the distribution of estimated CO_2 storage resouce in Niger Delta fields is skewed towards smaller sizes, with about 80% of the fields having less than 20 Mt resource. However, in the remaining 20%, there are several larger fields, with 30 Mt or more estimated CO_2 storage resource, that comprise almost half of the 3.4 Gt storage resource identified by this study for depleted and near-depleted fields in Niger Delta.

Figure 6.26. Location of Nigeria's depleted oil and gas fields. Largest circles are sites over 100 Mt.



Source: BCG

Figure 6.27a. Nigeria's abandoned oil and gas fields over 10 Mt resource showing high, medium and low resource estimations. Offshore and onshore fields are indicated

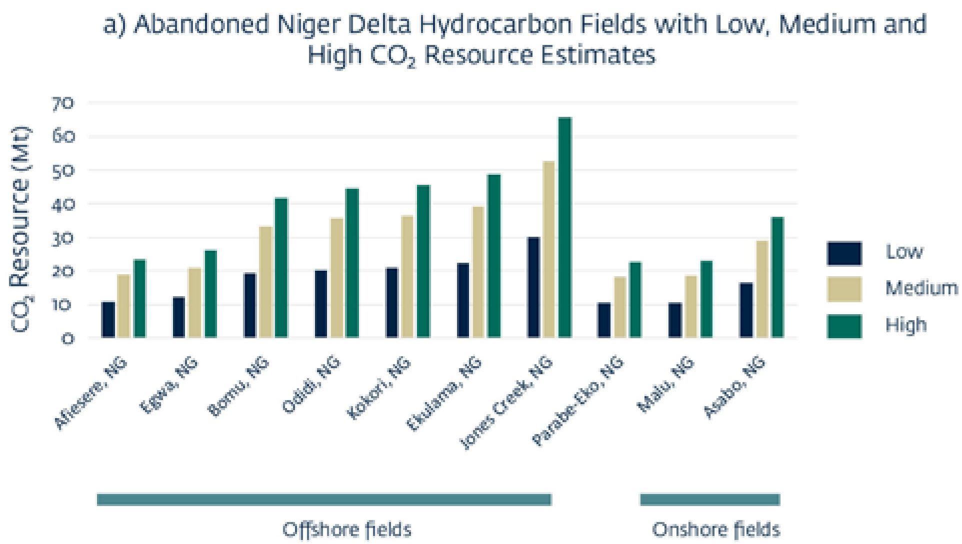
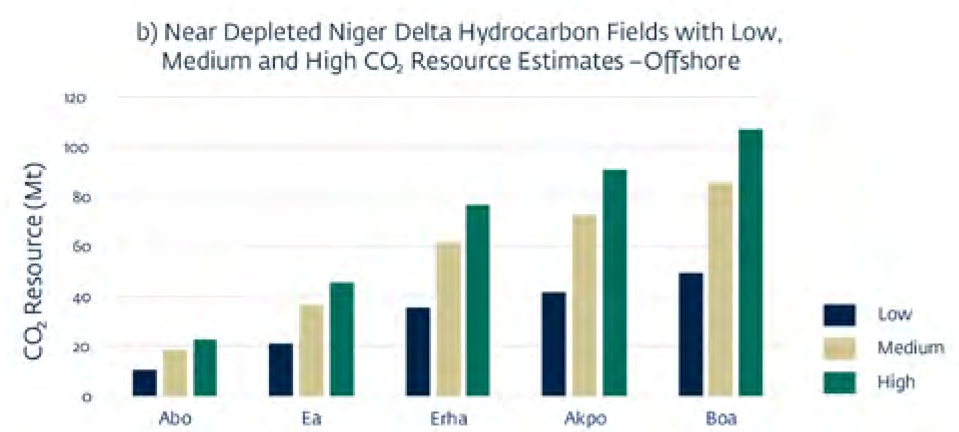


Figure 6.27b. Nigeria's offshore near depleted oil and gas fields over 10 Mt resource showing high, medium and low resource estimations for offshore.



Source: BCG

Figure 6.27c. Nigeria's onshore near depleted oil and gas fields over 10 Mt resource showing high, medium and low resource estimations.

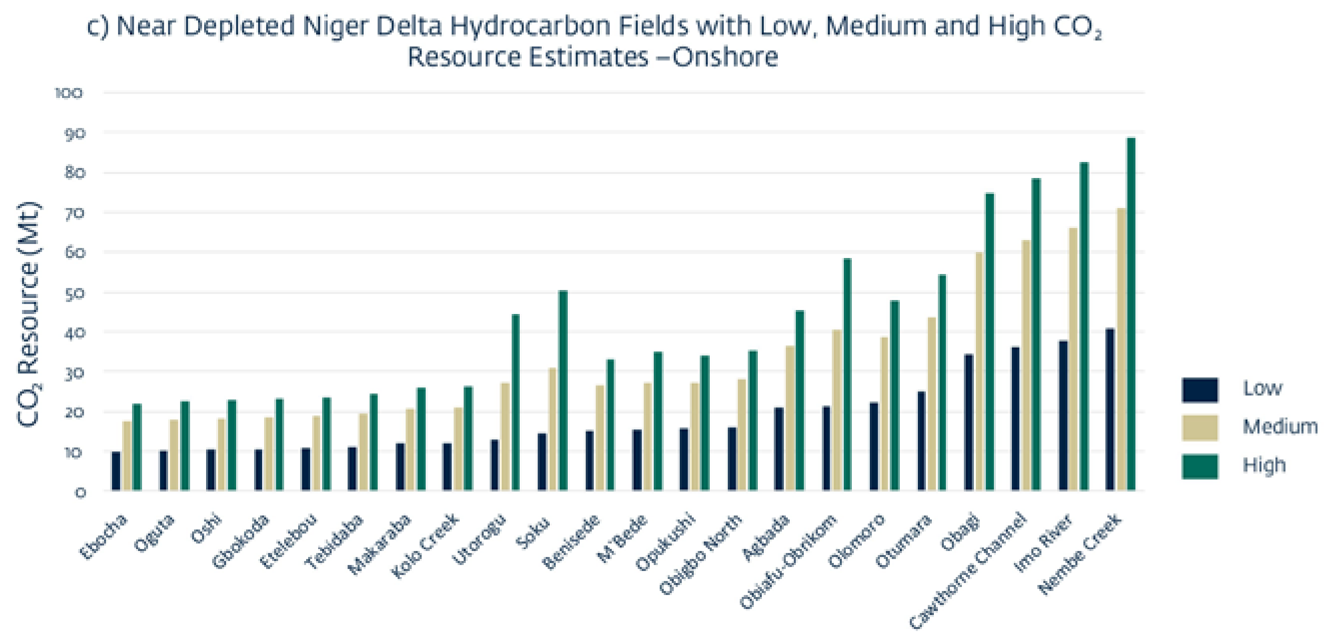
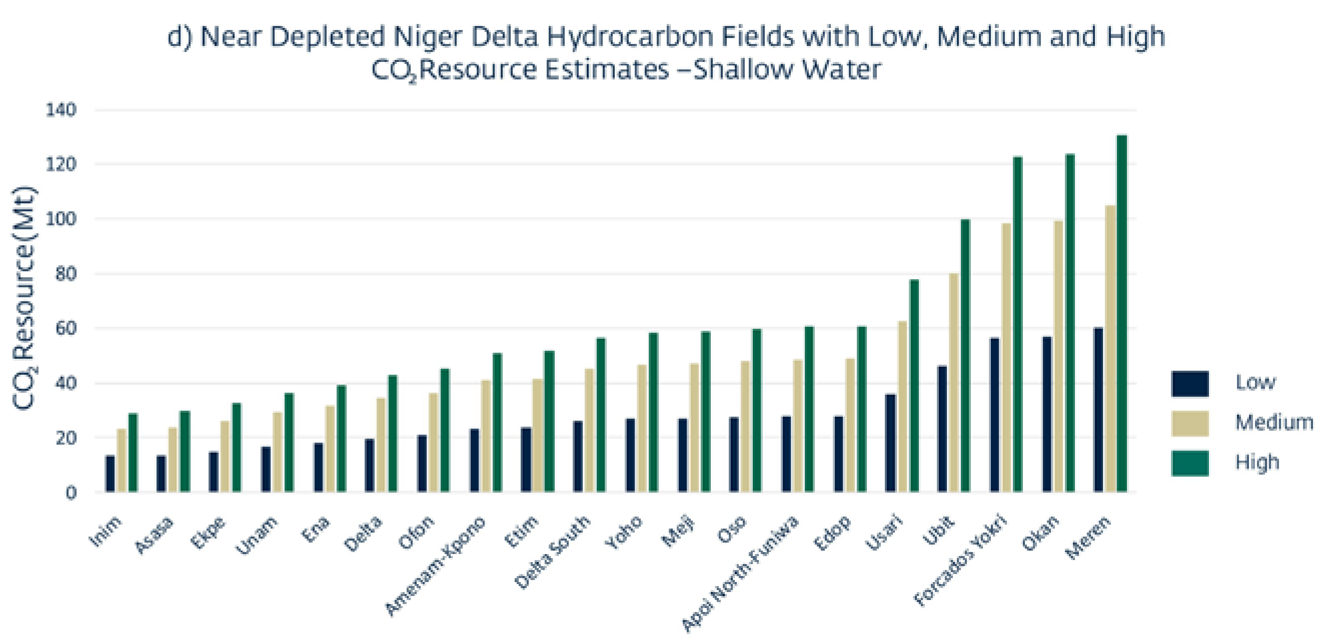


Figure 6.27d. Nigeria's shallow water near depleted oil and gas fields over 10 Mt resource showing high, medium and low resource estimations.



Source: BCG

6.10 Unconventional Storage Options

6.10.1 Storage in Basalt Formations

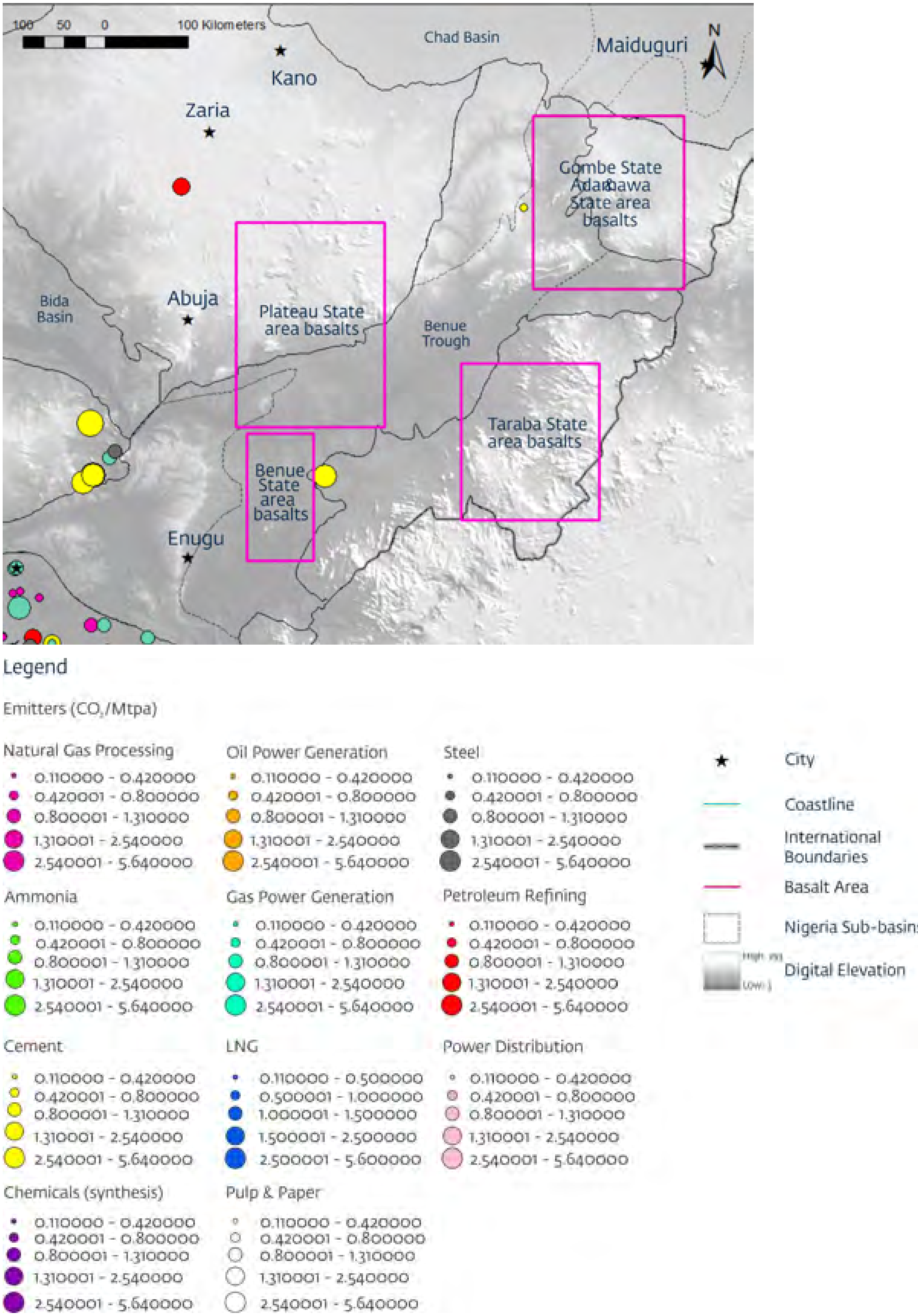
CO_2 can also be injected for storage into basalt formations (extrusive volcanic rock). The process here involves carbon mineralisation by the formation of solid carbonate minerals through the reaction of CO_2 with rocks rich in calcium or magnesium. The best sources of calcium and magnesium are mafic and ultramafic rocks (mantle peridotite, basaltic lava, and ultramafic plutons) (Keleman et al. 2019).

The most significant benefit of CO_2 storage in basalt, as opposed to sedimentary reservoirs, is the rapid mineralisation of the CO_2 into carbonate minerals. This is due to the abundance of metallic cations found in mafic and ultra-mafic rocks. Rapid mineralisation greatly reduces the risk of leakage over time. Although this method of CO_2 sequestration has been known for many years, only two pilot projects in the world have so far enabled injection into basalt formations. They are the CarbFix project in Iceland (Snæbjörnsdóttira, et al. 2018) and the Wallula project in the USA (McGrail et al. 2017). The limited progression of this method is mainly due to the complexity of the mineral interactions in the rock and the difficulty to estimate the storage resource in the long term. Although basalt is a suitable rock for rapid carbon mineralisation, the lack of effective monitoring techniques and the amount of water required for injection are two major challenges that need to be addressed. (Raza et al. 2022).

Figure 6.28. Basalt locations in Nigeria.

Map is provided courtesy of the NGSA.

Figure 6.29. Location of basalt regions in Nigeria and proximity of CO_2 emissions sources



Source: Halliburton, BCG

6.10.2 Basalt CO_2 Storage Potential in Nigeria

Nigeria has several basalt formations that may be able to be developed for CO_2 storage, particularly in the Jos Plateau, Adamawa, Gombe, Taraba and other volcanic regions. Further assessments are needed to identify the geological suitability of these formations for CO_2 storage.

Figure 6.28 shows a map of the location of areas in Nigeria with basalt resources. These basalt formations are generally far from emissions sources however (Figure 6.29).

6.10.3 Storage in Non-Mineable Coal Seams

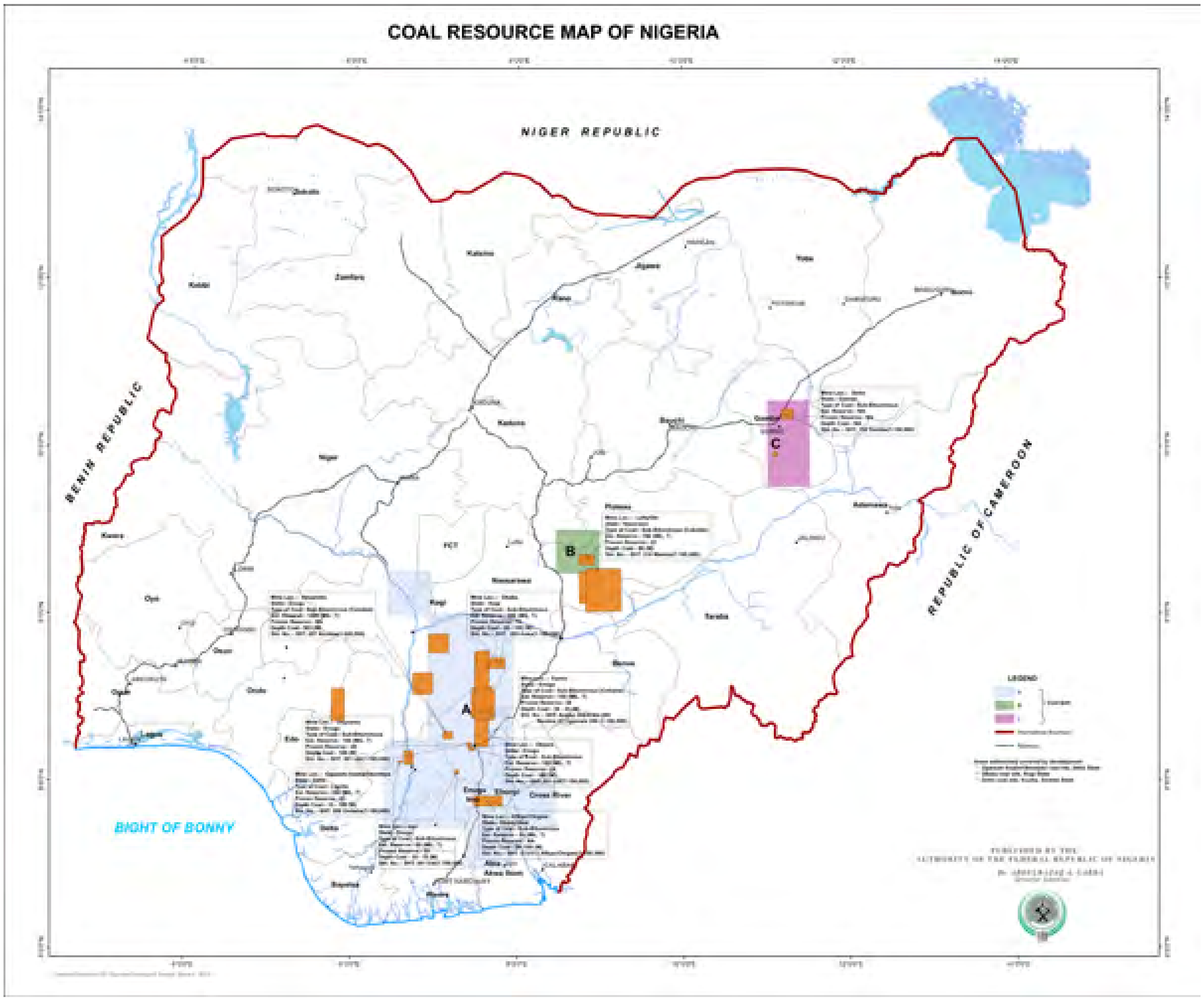
Coal formations can also be used to store CO_2 in coal seams or as part of enhanced coal-bed methane production (CO_2-ECBM). This is analogous to CO_2 EOR. When CO_2 is injected into coal seams, it is adsorbed and displaces methane which can then be used as a resource. However, the released methane is a greenhouse gas by-product and burning it for fuel will produce some CO_2. By capturing CO_2 from the fossil fuel emissions, a reduction of CO_2 released to the atmosphere can be achieved. Factors affecting the success of this process relate to the permeability of the coal, the pressure, temperature, moisture content and rank of the coal, the local hydrogeology and the structural setting of the coal seam (Shi and Durucan 2005). Projects relating to injection in coal and CO_2-ECBM are limited. The Allison Pilot Project in the San Juan Basin, New Mexico, was the world's first trial of this process. The project started in 1995 and was suspended in 2001. Various other pilot projects have been conducted over the past two decades in Albetra (Canada), the Southern Bowen Basin in Australia, the Silesian Coal Basin in Poland, the Qinshui Basin in China, Yubari and Hokkaido in Japan and the Permian and Appalachian basins, USA (Leung, et al. 2014).

6.10.4 Coal Seam CO_2 Storage Potential in Nigeria

Nigeria has a number of coal seams that may be able to be developed for CO_2 storage or CO_2-ECBM. Figure 6.30 shows a map of the location of areas in Nigeria with coal resources. Coals with a lower rank such as lignite and sub-bituminous coals generally have higher porosity and permeability which means they may present better CO_2 storage resources (Kolak and Burruss 2004). Depth is also important since coal beds found at greater depths have higher pressures which can increase the storage capacity of coal seams, however, permeability can decrease with depth (Shi and Durucan 2005).

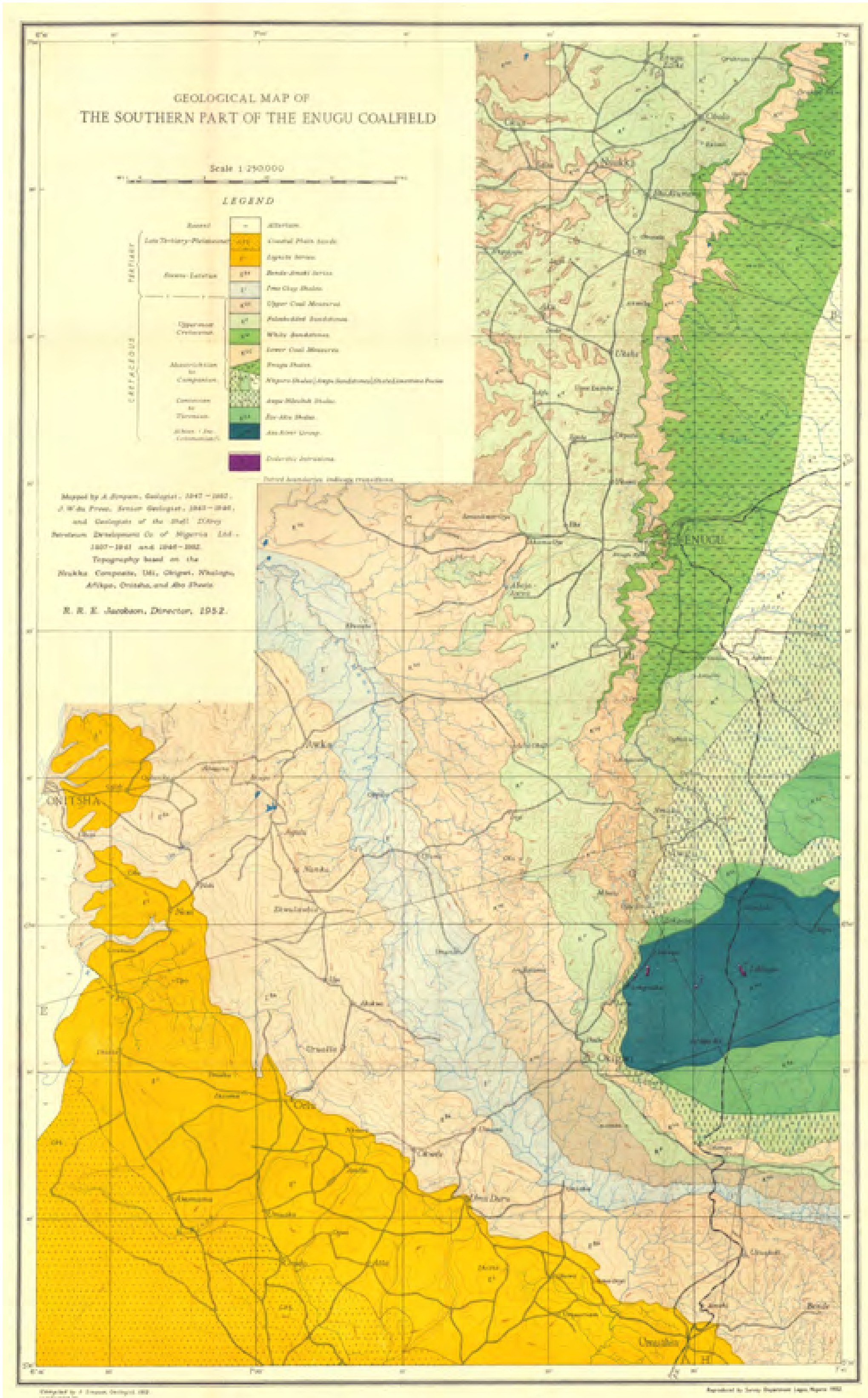
As yet, studies are limited on this method for CO_2 storage in Nigeria, however there have been studies conducted in the Anambra Basin, (Fagorite et al. 2023). The coal's rank, grade, and type were determined using proximate, ultimate, petrographic, FT-IR and SEM-EDS analyses. Coal seam III in the Enugu area (Figure 6.31) was identified as the most promising capacity with an estimated of 5700 Mt of potential resource (Fagorite et al. 2023)

Figure 6.30. Coal resource map of Nigeria.



Source: Map is provided courtesy of the NGSA.

Figure 6.31. Geological map of the coal seams in the Enugu area. Coal Seam III lies to the west of Engu and Eke.



Source: Map is provided courtesy of NGSA

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7 Glossary

Definitions:

Aquifer drive	Mechanism whereby fluid is driven through a reservoir by an active aquifer.
Argillaceous	Containing particles of silt or clay of a size less than 0.625 mm (pertaining to sedimentary rock).
Basalt	A fine-grained extrusive igneous rock formed from the rapid cooling of low-viscosity lava rich in magnesium and iron (mafic lava) exposed at, or very near, the surface.
Basaltic lava	Molten or partially molten rock (magma) which has been expelled to the surface. Mafic or basaltic lavas are typified by relatively high magnesium oxide and iron oxide content.
Basement	Crystalline rocks lying above the mantle and beneath all other rocks and sediments.
Basin	A depression or dip in the Earth's surface where sediments accumulate.
Capillary entry pressure	The pressure that a non-wetting fluid (e.g. CO_2) must overcome to displace water held tightly by capillary forces in the pores of a rock or sediment.
Cement (geological)	The binding material in sedimentary rocks which precipitates between grains from pore fluids. Calcite and quartz are common cement-forming minerals.
Cluster project	A group of CO_2 emitters and /or multiple storage locations using shared transportation infrastructure.
CO_2 EOR	Process of injecting CO_2 for enhanced oil recovery from existing fields. This increases the overall pressure of an oil reservoir, forcing the oil towards the production well(s).
Coal rank	The measure of the degree of organic metamorphism (coalification) of a coal.
Common Risk Segment mapping (CRS)	Technique used by oil companies to evaluate the petroleum potential of a sedimentary basin.
Compression	Decrease in volume of any object or substance resulting from applied stress. Geological forces which operate to compress rocks are due to burial or tectonic forces.
Concentration of emission streams	CO_2 concentration in flue gas
Contact angle	The angle between a liquid drop and a solid surface where they meet.

Deltaic	Sediments that originate from river delta environments.
Diagenetic	Physical and chemical changes occurring during the conversion of sediment to sedimentary rock.
Dissolution (CO_2)	Refers to the process where CO_2 gas dissolves in water to form a solution.
Drainage networks	The collection of all the channels in a drainage basin.
Evaporite	Sedimentary deposit resulting from concentration and crystallization of minerals, due to evaporation of water solution. In the geological context typically refers to salt deposits.
Extensional tectonics	Processes associated with the stretching of the Earth's crust.
Facies	A body of rock with specified characteristics.
Fairway	The spatial extent of a region where a particular geological feature is likely to occur.
Fault	Fracture or discontinuity in a volume of rock caused by mass rock movement.
Fold	Curve in a volume of rock caused by mass rock movement.
Geochemistry	The chemical composition of rocks and minerals.
Geomechanics	The study of the mechanical state of rocks and the processes occurring within them under the influence of natural and external physical factors.
Geothermal gradient	The rate of temperature change with respect to increasing depth below the Earth's surface.
Growth faulting	Extensional faults which initiate and evolve at the margins of continental plates.
Heterogeneity	Variations in rock properties within a rock formation.
Hydrogeology	Distribution and movement of groundwater in the soil and rocks of the Earth's crust (commonly in aquifers).
Hydrostatic pressure	The normal pressure for a given depth, or the pressure exerted per unit area by a column of freshwater from sea level to a given depth.
Industrial CO_2	Industrial processes and product use (IPPU) and fuel combustion related to industrial processes.
Intercalated	Layers of material which exist between layers of rock with different characteristics.
Interfacial tension	A property of the interface between two immiscible fluid phases.

Inversion	The relative uplift of a sedimentary basin or similar structure resulting from crustal shortening.
Lacustrine sediments	Sedimentary rock formations which were formed at the bottom of ancient lakes.
Mafic	Minerals or igneous rocks composed of minerals that are rich in iron and magnesium, dense, and typically dark in color.
Mantle peridotite	A dense, coarse-grained igneous rock consisting mostly of the silicate minerals olivine and pyroxene. It is the dominant rock of the upper part of the Earth's mantle.
Metallic cations	Positively charged ions formed when a metal loses its electrons.
Net:Gross	The proportion of total rock thickness formed by the reservoir rock.
Non-wetting	When one fluid preferentially covers the surface, it is called the wetting fluid and the other fluid is called the non-wetting fluid.
Orogenic	A process in which a section of the earth's crust is folded and deformed by lateral compression to form a mountain range.
Over-pressure	When pore or subsurface pressure exceeds the normal hydrostatic pressure at a given depth.
Permeability	The ability of a rock to allow gases or liquids to flow through it.
Petroleum system	A body of active source rock and all genetically related oil and gas accumulations.
Pinch-out	Point where a lithologically distinct body of rock thins to a feather edge and disappears, so that the underlying and overlying strata separated by the pinching out stratum come into direct contact.
Play	One or more geologically related prospects.
Pluton	A mass of magnetic rock that has solidified below the surface of the earth.
Pore radius	The radius of the largest sphere which will fit inside a rock's pore space.
Porosity	The percentage of void space in a rock.
Progradation	The lateral building of sedimentary strata in a seaward direction.
Prospect	A structural or stratigraphic trap that must be evaluated to determine if it could contain commercial quantities of the target fluid (in this case CO_2).
Re-pressurisation	The process of increasing the pressure within the reservoir after it has been depleted of fluids.
Reservoir	A subsurface body of rock having sufficient porosity and permeability to store and transmit fluids.

Seal	A subsurface body of rock with low permeability that impedes the escape of fluids from a reservoir.
Seismically quiescent	A period of low seismic activity within a specific time interval.
Sequence stratigraphy	A branch of geology which subdivides and links sedimentary deposits into unconformity-bounded units (sequences) on a variety of scales.
Siliciclastic rocks	Non-carbonate clastic sedimentary rocks composed primarily of silicate minerals, such as quartz or clay. Siliciclastic rock types include mudstone, sandstone and conglomerate.
Source rock	A rock which has generated or could generate hydrocarbons. These often have low permeability.
Stratigraphy	A rock layer, or series of rock layers, of the same age.
Storage efficiency	Fraction of the storage capacity, storage resource, total pore volume, effective pore volume, bulk volume, and/or storable quantity expected to be used for storage by a specific project.
Supercritical carbon dioxide (CO_2)	A fluid state of carbon dioxide where it is held at or above its critical temperature and critical pressure.
Supercritical fluid	A substance at a temperature and pressure above its critical point.
Sweep efficiency	Measure of the effectiveness of an enhanced oil recovery process that depends on the volume of the reservoir contacted by the injected fluid.
Syn-rift	Refers to rocks deposited during an extensional geological regime (active rifting of two plates).
SWPM	Sealed wellbore pressure monitoring is a low-cost, nonintrusive method used to evaluate and quantify fracture-growth rates and fracture-driven interactions during a hydraulic stimulation.
Tectonic activity	Dynamic processes which shape the Earth's crust.
Tethys Ocean or Sea	A prehistoric ocean during much of the Mesozoic Era and early-mid Cenozoic Era. It was the predecessor to the modern Indian Ocean.
Thermal subsidence	Mechanism of subsidence in which conductive cooling of the mantle thickens the lithosphere and causes it to decrease in elevation.
Transgressive	A geological event during which sea level rises relative to the land.
Transmissive fault	Fault which conducts fluids.
Ultramafic rocks	Igneous and meta-igneous rocks with a very low silica content (< 45%), generally >18% magnesium oxide, high iron oxide, low potassium, and are usually composed of >90% mafic minerals.
Unconformity	A geological contact caused by a period of erosion or a pause in sediment accumulation separating two rock masses of different ages.

Up-dip	Located up the slope of a dipping plane or surface (relative to another point).
Wettability	The ability of a liquid droplet to maintain or spread on a solid surface.

Units:

^0C	Degrees centigrade
Gt	Gigatons
Ktpa	Thousand tonnes per annum
Kg/m^3	Kilogram per cubic meter
m	Meter
m^2	Square meters
Ma	Million years
μD or mD	Millidarcies
μm	Micrometre
mm	Millimetres
mg/l	Milligram per liter
MPa	Mega Pascals
Mt	Mega Tones
Mtpa	Million tonnes per annum
Mt/year	Mega tonnes per year
NGR	Net Gross Ratio
p.a.	Per annum
ppm	Part per million
%	Percent sign
t	Tonne
Tcf	Trillion cubic feet
USD	United States Dollars

Acronyms:

BCG	Boston Consulting Group
BECCS	Bioenergy with carbon capture and storage
CBM	Coalbed methane
CCS	Carbon capture and storage.
CCRS	Composite common risk segment mapping
CCUS	Carbon capture utilization and storage
CO_2	Carbon dioxide
CO_2/Mtpa	Annual emission of CO_2 in million tonnes
CO_2-ECBM	(CO_2)-enhanced coalbed methane recovery
CO_2 EOR	CO_2 enhanced oil recovery
CSLF	Carbon Dioxide Sequestration Leadership Forum
DPI	Department of Primary Industries
DOE	United States Department of Energy
ECC	East Coast Cluster
EES	Environmental evaluation study
EOR	Enhanced oil recovery
EPA	Environmental Protection Agency
ETP	Energy Transition Plan
ETS	Emissions Trading System
FEED	Front End Engineering and Design
FGN	Federal Government of Nigeria

FID	Financial Investment Decision
FT-IR	Fourier-transform infrared spectroscopy
GCCSI	Global CCS Institute
GDE map	Gross depositional environment map
GDP	Gross domestic product
GHG	Greenhouse gases
GIS	Geographic information system
ICS	International Commission on Stratigraphy
IEA	International Energy Agency
IEAGHG	IEA Greenhouse Gas R&D Programme
IPCC	Intergovernmental Panel on Climate Change
IPPU	Industrial processes and product use
ISO	International Standard Organization
ISO/TC	ISO Technical Committee
ITA	International Trade Administration
LCFS	Low Carbon Fuel Standards
LNG	Liquified natural gas
MEG	Monoethylene Glycol
NGL	Natural gas liquid
MIT	Massachusetts Institute of Technology
MMV	Monitoring, measuring and verification

NCCC	National Council on Climate Change
NDC	Nationally determined contributions
NGR	Net gross ratio
NESREA	National Environmental Standards and Regulations Enforcement Agency
NETL	National Energy Technology Laboratory
NGSA	Nigeria Geological Survey Agency
NIMASA	Nigerian Maritime Administration and Safety Agency
NMDPRA	Nigerian Midstream and Downstream Petroleum Regulatory Authority
NNPC	Nigerian National Petroleum Corporation
NOSDRA	National Oil Spill Detection and Response Agency
NUPRC	Nigerian Upstream Petroleum Regulatory Commission
NPCC	National Policy on Climate Change
NZE	Net zero emission
OGCI	Oil & Gas Climate Initiative
OPEC	Organization of the Petroleum Exporting Countries
PCS	Project concept screening
PERA	Preliminary environmental risk assessment
PET	Polyethylene terephthalate
PIA	Post impact assessment study
PISC	Post injection site closure
PRMS	Petroleum resource management system
PVC	Polyvinyl chloride
SEM-EDS	Scanning electron microscopy with energy-dispersive X-ray spectroscopy
SCADA	Supervisory control and data acquisition

SRMS	Storage resource management system
SRW	Southern Rural water
SWPM	Sealed wellbore pressure monitoring.
U.N.	United Nations
UNFCCC	United Nations Framework Convention for Climate Change
VSP	Vertical seismic profile
WEF	The World Economic Forum

8 Appendix 1: Nigeria's Sources of CO_2

8.1 Methodology

Step 1 – Emitters List

A partnership between Boston Consulting Group (BCG) and the Oil & Gas Climate Initiative (OGCI) led to the development of the Energy Transition Hub Tool (also referred to as Hub Tool), which provides geospatial insight into CCUS and optimises the hub techno-economics. The Hub Tool is underpinned by a robust dataset of clearly defined sources.

The Nigerian dataset from the BCG Hub Tool is sourced from a selection of credible sources (Table 8.1), which include institutional global data, sector-specific global data, and private knowledge banks.

A further step of project-specific secondary research was conducted to address potential concerns on availability and reliability of the data obtained from global databases.

The project-specific secondary research gathered intelligence from:

- BCG's Industrial Goods (IG) practice area knowledge team and experts.
- Company websites.
- Company reports (e.g. annual reports).

Table 8.1. Institutional global data sources

Data Subject	Source	Coverage
Refineries	GlobalData	Global
Cement	Global Cement Directory	Global
Chemicals	DwCP	Global
Iron and steel	PlantFacts	Global
Petrochemical	DwCP; IHSMarkit	Global
Power	UDI	Global
Natural gas processing	GlobalData	Global
Aluminium	Wood Mackenzie	Global
Liquid natural gas (LNG) processing	CEDIGAZ	Global

- Press releases and other media coverage.
- Agency and regulator websites (e.g. NERC website).
- Agency and regulator reports (e.g. NEITI report, NNPC Annual Statistical Bulletin).
- Local business directories.
- Location verification via Earth mapping applications with satellite images and aerial photography.

Step 2 - Characterize Emitters

Characterization of CO_2 emitters concerned the determination of the availability of attributes required to satisfy objectives of the study, followed by project-specific secondary research to qualify or quantify those attributes.

A listing and description of applied CO_2 emitter attributes are given below:

- Facility name.
- Facility operator.
- Facility location.
- Sector: chemical manufacture, cement manufacture, crude refining, etc.
- Operator archetype refers to whether the facility operator is being operated by a government company/ agency or by a non-government entity (i.e. publicly listed company, privately owned company, etc.).
- Facility age denotes number of years that a facility has been in operation.
- Operational status marks whether a facility is in active service or temporarily shut.
- Fuel/ feedstock type refers to source(s) of energy for combustion such as coal, natural gas or refined petroleum products.
- CO_2 emission is an estimate of carbon dioxide emitted by the facility based on parameters such as fuel/ feedstock, industry sector and production capacity for products. CO_2 emission is estimated by application of BCG's proprietary technology-driven algorithms and pertains to capacity of facilities rather than their operating level. The year 2019 was adopted as the base year to better represent the facilities' CO_2 emission capacity, given that industrial activities in later years 2020-2021 were impacted due to COVID-19.
- Concentration streams are points along the manufacturing process where CO_2 is expelled to the atmosphere. These are typically flue stacks.

Step 3 - Validate and Refine Emitter List and Attributes.

Two steps were used to validate and refine the Nigeria CO_2 emitter database from Steps 1 and 2:

- Benchmarking of aggregated CO_2 estimates against independent sources.
- Validation of database entries by stakeholders, with stakeholders being the facility operators or agencies and regulators related to them.

For benchmarking, 2019 estimates from four independent reports were referenced (in alignment with the base year adopted for the CO_2 emitter database):

- Nigeria's Second Biennial Update Report (BUR2) to the UNFCCC, published June 2021 (data up to 2017).
- Nigeria 2019 Extractive Industries Transparency Initiative (NEITI), published July 2021.

- ClimateTrace – Web-based global GHG database reporting country-level data and sector-level estimates.
- ClimateWatch – Web-based global NDC tracker and GHG database reporting current and historical country-level GHG estimates.

Data was sought on the following topics:

- Name(s) of facility(ies) and their location(s).
- Year of commission.
- Date of most recent refurbishment or upgrade.
- Production capacity.
- Capacity utilization.
- Specifics of manufacturing processes.
- Fuel and/ or feedstock(s) utilized.
- Estimated or measured CO_2 emission per annum (if available).
- Number and types of CO_2 emission streams e.g., fuel combustion exhaust.
- CO_2 concentration for each emission stream (if available).
- Availability of land for CCS infrastructure.
- Access to low pressure stream.

8.2 References

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9 Appendix 2: Storage Atlas Construction Methodology

9.1. Methodology

A variety of geological workflows were applied to assess the CO_2 storage potential in Nigeria. References are provided in the body of the text for further information on these techniques.

Countrywide screening for CO_2 storage in saline aquifers requires a consistent regional perspective and stratigraphic framework to identify potential reservoir-seal pairs and rapidly screen for viable sites. Halliburton's Neftex Predictions service was used to provide relevant content and insights, including specific data and tools aimed at composite common-risk segment (CCRS) mapping and proprietary workflows for CO_2 storage screening. The data used in the construction of the Atlas and it implications are discussed in Section 9.2.

9.1.1 Regional Screening

Initial regional screening focused on three key parameters:

- Depth/ pressure.
- Temperature.
- Present-day tectonism.

Temperature and depth/ pressure are important parameters with which to assess the potential for injected CO_2 to act as a supercritical fluid. CO_2 in its supercritical phase will behave as a gas and readily infill pore space but has the density of a liquid (Bachu 2003) and is less buoyant. Therefore, once injected, supercritical CO_2 will migrate more slowly (compared to CO_2 gas) through the reservoir and have a greater chance of being successfully captured and retained and is thus generally preferred for CO_2 storage. In addition, the increased density of supercritical CO_2 results in an increased mass of CO_2 stored compared to CO_2 storage in a gaseous state.

For CO_2 to behave as a supercritical fluid, temperature must exceed 31.1°C and pressure should be greater than 7.38 MPa. This is known as the critical point (i.e. the point at which CO_2 is in a supercritical phase). These parameters were analyzed utilizing Neftex® Predictions datasets and combined to reflect areas where CO_2 could be stored in a supercritical state in the subsurface. Temperature was assessed utilizing surface temperature and geothermal gradient maps, whilst a pressure of 7.38 MPa is equivalent to approximately 800 m depth in a hydrostatically pressured basin. A proprietary Depth to Basement Map was used screen for areas where the total sedimentary pile thickness is greater than 800 m and also expected to be at temperatures exceeding 31.1°C.

Understanding present-day tectonism is an important screening parameter as both surface infrastructure and subsurface seal integrity need to be stable and intact to capture and store CO_2 long term (hundreds to thousands of years). Therefore, tectonically quiescent areas are more suitable than those that are active.

9.1.2 High-Level Basin Review and Play Identification

Following the selection of suitable sedimentary basins for assessment via regional screening, the overall geology and tectonic history of Nigeria was reviewed. Tectonic events during the geological history of Nigeria exerted a primary control on the distribution, type and structural aspects of sedimentary rocks within the country. This geodynamic evolution directly impacted the distribution of plays, and the quality, thickness and continuity of reservoirs and seals. In addition, faulting and folding could help to create traps for CO_2 but could also pose a risk for CO_2 leakage.

Neftex® Predictions geodynamic model for the Phanerozoic, past plate tectonic configurations, regional stress patterns and likely loci for tectonic activity were evaluated. This approach provided regional context to the limited well and map-based data available to the project, allowing extrapolation beyond areas of data control on the expected accommodation space, sediment type and sediment source areas. The geodynamic model was integrated with the proprietary Neftex® Predictions sequence stratigraphic model to provide a consistent structural and stratigraphic framework within which to interpret the available geological data.

In addition, utilizing oil and gas field datasets (supplied by NODSRA, NUPRC, and supplemented with Neftex® Predictions geological data) allowed review of the exploration status of sedimentary basins to highlight which areas contained existing hydrocarbon fields and were therefore known to have viable reservoirs, seals, traps and infrastructure. This dataset was used to highlight the ability of a basin to store buoyant fluids for a prolonged period of geological time and which, therefore, may contain suitable sites for future CO_2 storage.

Based on the parameters outlined in Table 9.1, the prospective sedimentary basins of Nigeria were reviewed and an initial list of potential reservoir units suitable for CO_2 storage with overlying sealing formations (together known as plays) was compiled.

Table 9.1. The initial screening rationale used to assess basins for CO_2 storage.

Criteria	Rationale
Basin exploration status	A basin which has received a high level of investment for oil and gas exploration will have a significant amount of subsurface data available for CO_2 storage assessment. Basins that have not been actively explored would require initial capital investment in data acquisition to enable even a cursory storage assessment. This is unlikely to prove economically viable and will delay any pilot project activity. Although data availability decreases uncertainty of the analysis, it does not necessarily decrease the risk.
Data coverage	High data coverage across the basin means that all areas and stratigraphic levels with potential for CO_2 storage can be analyzed and thus screening outputs for these areas carry a lower degree of uncertainty.
Oil and gas fields	The presence of oil and gas fields demonstrates that viable plays and traps exist in a basin for subsurface storage of liquids and gases, e.g. that containment within daughter units in the same play is possible in the basin.
Known aquifers	The presence of known aquifers demonstrates that viable plays may exist in a basin for subsurface storage of injected fluids.
Tectonic type	Broad tectonic type allows an assessment of the likely presence, distribution and density of faults (the potential for future fault reactivation and risk of seal breach needs to be considered even at this scale).

9.1.3 Play-Level Geo-risk Assessment

After plays which met the regional screening criteria were identified, they were assessed at a basin scale for geological risk of economic CO_2 containment (“geo-risk”). This assessment was carried out using several categories based on published guidelines and best practices (IEA, 2009, CO_2Stored 2023). A qualitative approach was used to allow for assessment across basins with differing data availability and this was considered sufficient for this preliminary, high-level screening. For each assessed category, the number of papers used to support the assigned geo-risk was used as a proxy to categorise the uncertainty in the result. It is noted that one high quality-paper may add more value than several poorer quality ones; however, this proxy gives an overall measure of the amount of attention given to a play for comparative purposes. The table of geo-risk parameters and risk analysis are shown in Table 5.1 and Figure 5.11 in chapter 5.

9.1.4 Sequence Stratigraphy, GDE Mapping and Reservoir-Seal Fairway Mapping

Using a proprietary sequence stratigraphic model, the publicly available well and outcrop data for Nigeria were re-interpreted in a consistent country-wide schema. This allowed for improved mapping of the distribution of differing sedimentary rock types of the same age, also known as gross depositional environment (GDE) mapping. GDE mapping facilitates identification of areas where viable reservoir facies for potential CO_2 storage are overlain by a seal facies. These maps were further augmented by other publicly available data sets such as oil and gas field locations within the mapped sequence, formation properties, and the distribution of tectonic elements.

Each reservoir and seal pair typically comprised several sequence stratigraphic packages. The overall extent of the reservoir and seal intervals were derived from each of the GDE maps into stacked reservoir and seal presence maps. Reservoir and seal effectiveness was not considered for this analysis due to lack of data in some basins.

9.1.5 Depth Mapping

To map potential CO_2 storage fairways (the geographic area over which it is likely CO_2 can be stored long-term in the subsurface) for each of the identified plays, it was important to consider the depth to individual target reservoirs. This rapidly screened out areas within the basin where potential reservoir intervals were either too shallow, and therefore unable to facilitate supercritical storage of CO_2, or too deep to be economically viable.

Using available depth-related data such as wells, seismic, structural cross-sections and published maps (depth, isopach, isochore etc.), a regional depth framework was created for Nigeria.

The optimal depth interval to store CO_2 in the subsurface is generally considered to be between 800-2000 m. Deeper intervals may be suitable but are often considered to be less economically viable. Using the mapped structural depth surfaces, these thresholds were then applied to generate depth common risk segment (CRS) maps for each reservoir interval (see Chapter 6 for examples of CRS maps for plays in Nigeria).

9.1.6 CRS Mapping

Common risk segment (CRS) mapping is a process used to high-grade certain areas geographically. For each risk element a traffic light colour map is created (with green indicating a positive outcome, yellow indicating an average outcome and orange indicating a negative outcome). These maps are then “stacked” carrying through the highest risk area. For example, if an area is risked medium for reservoir presence, low for seal presence and high for depth, the overall risk assessment is high.

Using the parameters outlined in Table 9.2, this methodology was used to combine the outputs from stacked reservoir presence, stacked seal presence and depth CRS maps to generate composite common risk segment (CCRS) fairway maps for each of the highest ranked plays identified in the geo-risk assessment. The result is an indication of the potential CO_2 storage fairway (delineated in green) for a specific reservoir-seal pair (or play) (See Chapter 6 for CRS maps for Nigerian CO_2 Storage plays).

Table 9.2. Table of risk values assigned for CRS mapping.

Risk Element	Low Risk (Green)	Medium Risk (Yellow)	High Risk (Orange)	Rationale
Reservoir presence map	Marine, shoreface or lacustrine sandstone	Siltstone and shallow marine carbonate	Marine, shoreface and lacustrine shale	Bump et al. 2021
Seal presence map	Salt or marine, shoreface or lacustrine shale	Siltstone and marl	Marine and lacustrine carbonate and sandstone	Bump et al. 2021
Reservoir interval depth map	800-2000 m	2000-3000 m	<800 m or >3000 m	Bachu 2003; Chadwick et al. 2008

9.2 Data Constraint

This study made use of Neftex® Predictions datasets, proprietary tools developed in Esri ArcGIS® and additional publicly available data. All data were reinterpreted within a common sequence stratigraphic framework allowing for a unique and consistent analysis across the whole of Nigeria.

Table 9.3 below shows a summary of the Neftex® Predictions data used to constrain this Atlas. This was supplemented by additional data on oil and gas field locations from NOSDRA and reports on surface geology from NGSA.

Figure 9.1 Data used in this study.

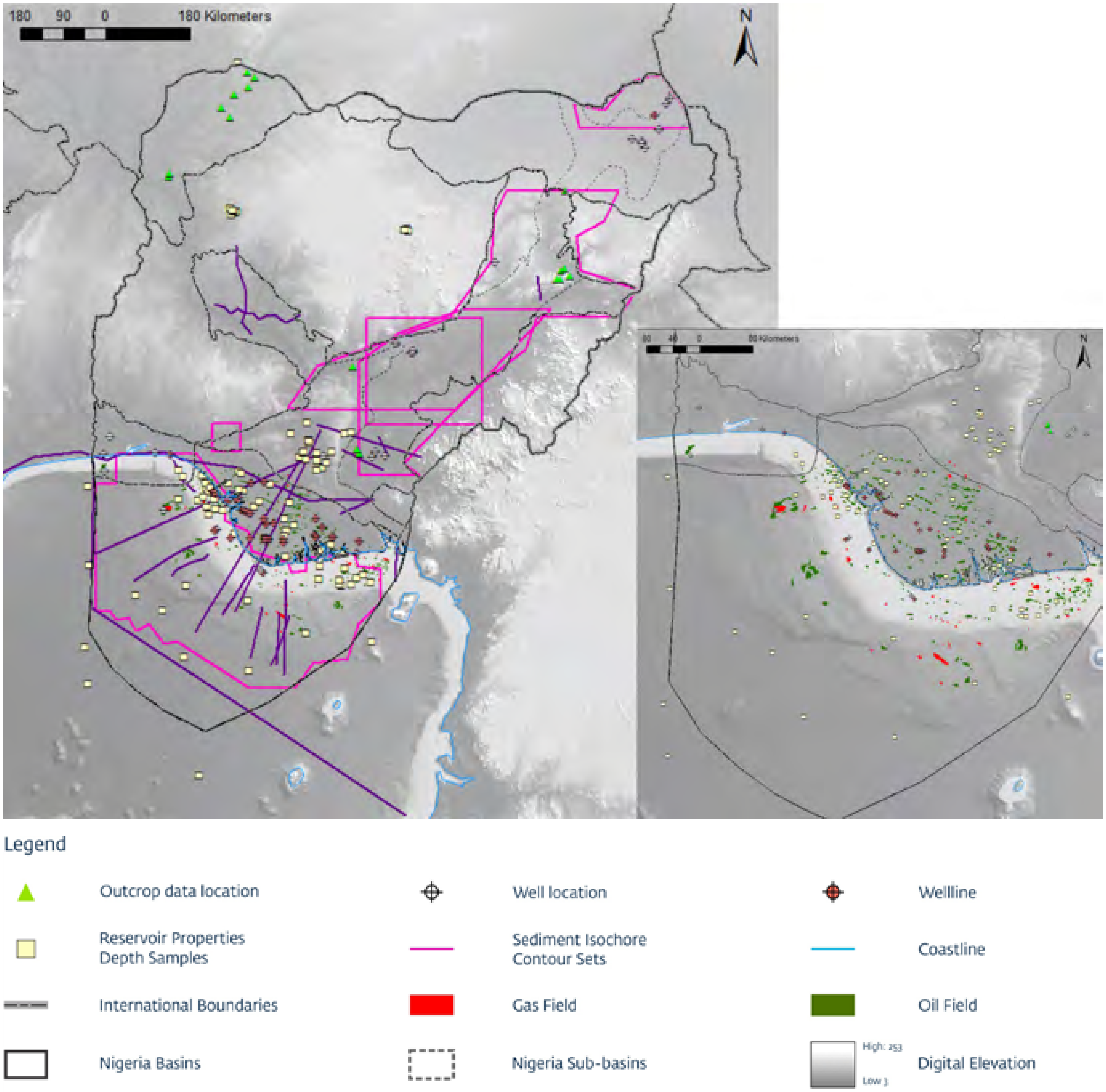

Table 9.3. Table of data types used in the construction of the maps and fairway analysis for CRS maps

Data/content type	Description
Geodynamic plate model	Model reviewed to define tectonic activity and faulting
Gross depositional environment (GDE) maps	17 maps integrated, reviewed and compiled
Regional depth maps	8 maps integrated, reviewed and compiled
Wells	91 wells reinterpreted to constrain GDE mapping effort.
Oil and gas field map	386 sequence stratigraphically constrained fields used to constrain GDE mapping effort
Porosity data	1937 data points used to constrain GDE mapping effort
Structural cross sections	13 used to constrain depth mapping
Structure depth maps	5 used to constrain depth mapping

9.3 References

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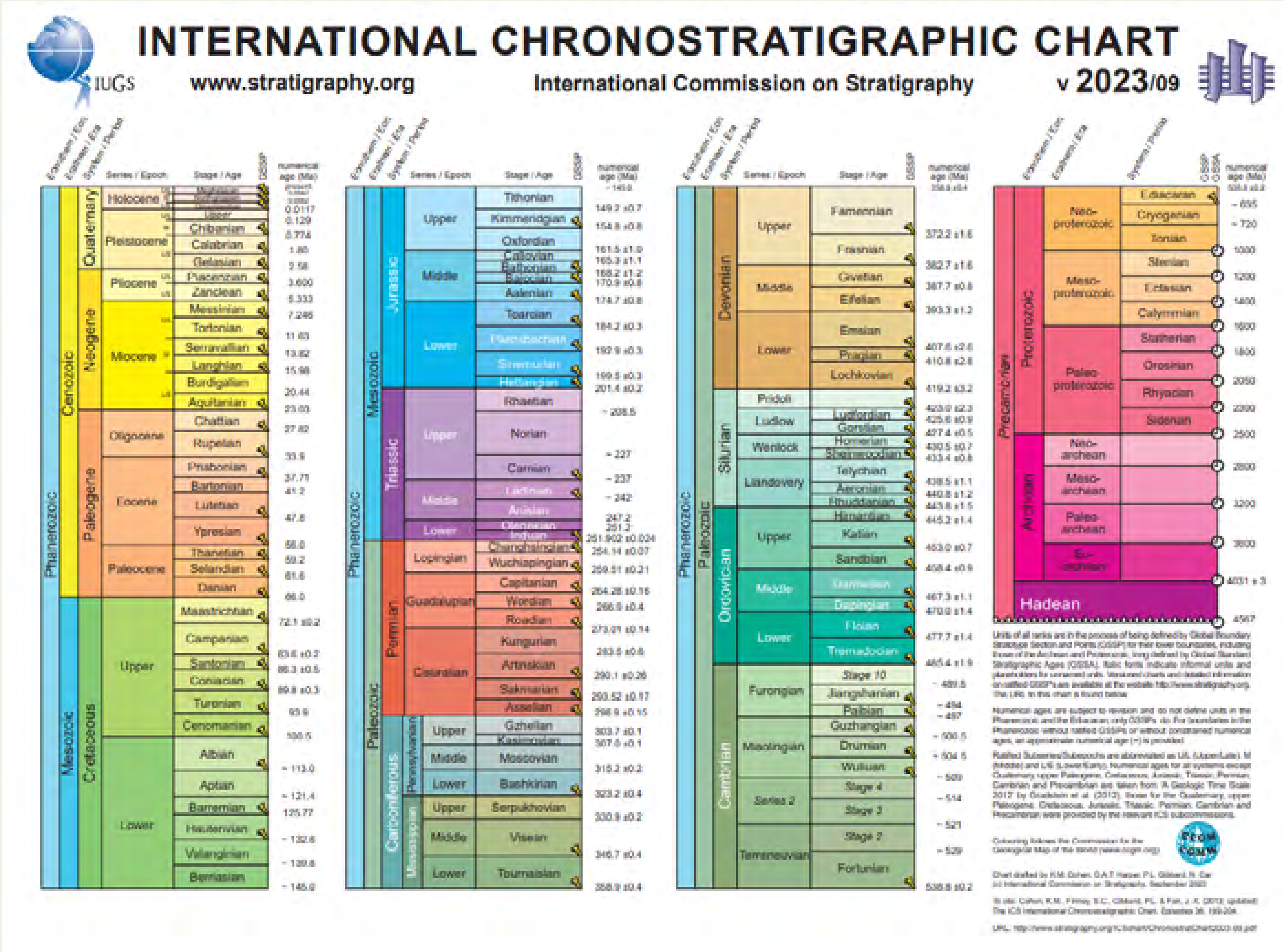
10 Appendix 3: International Chronostratigraphic Chart

The geological time scale is an extensive interval of time that represents distinct events in the Earth's history. It begins at the Archean Eon around 4 - 2.5 billion years ago and extends to the present day. This time scale is comprised of geological events or units which are classified into eons, eras, periods, epochs and stages. The units are a composition of the stratigraphy deposited over time which both characterizes and defines the geological units. The stratigraphy is dated by fossil remains in the rock and allows correlation between depositional and geological events across basins, regions and areas of the world. One of the most widely used standard time scales is the International Chronostratigraphic Chart, which is maintained by the International Commission on Stratigraphy (ICS).



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