A REGIONAL ASSESSMENT OF THE POTENTIAL FOR CO_2 STORAGE IN THE INDIAN SUBCONTINENT

Technical Study

Report No. 2008/2

May 2008

INTERNATIONAL ENERGY AGENCY

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. The IEA fosters co-operation amongst its 26 member countries and the European Commission, and with the other countries, in order to increase energy security by improved efficiency of energy use, development of alternative energy sources and research, development and demonstration on matters of energy supply and use. This is achieved through a series of collaborative activities, organised under more than 40 Implementing Agreements. These agreements cover more than 200 individual items of research, development and demonstration. The IEA Greenhouse Gas R&D Programme is one of these Implementing Agreements.

ACKNOWLEDGEMENTS AND CITATIONS

This report was prepared as an account of the work sponsored by the IEA Greenhouse Gas R&D Programme. The views and opinions of the authors expressed herein do not necessarily reflect those of the IEA Greenhouse Gas R&D Programme, its members, the International Energy Agency, the organisations listed below, nor any employee or persons acting on behalf of any of them. In addition, none of these make any warranty, express or implied, assumes any liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product of process disclosed or represents that its use would not infringe privately owned rights, including any parties intellectual property rights. Reference herein to any commercial product, process, service or trade name, trade mark or manufacturer does not necessarily constitute or imply any endorsement, recommendation or any favouring of such products.

COPYRIGHT

ACKNOWLEDGEMENTS AND CITATIONS

This report describes research sponsored by the IEA Greenhouse Gas R&D Programme. This report was prepared by:

British Geological Survey
Keyworth
Nottingham
NG12 5GG

The principal researchers were:

- S Holloway
- A Garg
- M Kapshe
- A S Pracha
- S R Khan
- M A Mahmood
- T N Singh
- K L Kirk
- L R Applequist
- A Deshpande
- D J Evans
- Y Garg
- C J Vincent
- J D O Williams

To ensure the quality and technical integrity of the research undertaken by the IEA Greenhouse Gas R&D Programme (IEA GHG) each study s managed by an appointed IEA GHG manager. The report is also reviewed by a panel of independent technical experts before its release.

The IEA GHG manager for this report: John Gale

The expert reviewers for this report:

- Stefan Bachu, ERCB, Canada
- John Bradshaw, Geoscience Australia, Australia
- Rajesh Pawar, LANL, USA
- Sankar Battacharya, IEA, France

The report should be cited in literature as follows:

IEA Greenhouse Gas R&D Programme (IEA GHG), “A Regional Assessment of the Potential for CO_2 Storage in the Indian Subcontinent”, 2008/2, May 2008.

Further information or copies of the report can be obtained by contacting the IE Greenhouse Gas R&D Programme at:

IEA Greenhouse Gas R&D Programme, Orchard Business Centre, Stoke Orchard, Cheltenham, Glos., GL52 7RZ, UK
Tel: +44 1242 680753 Fax: +44 1242 680758
E-mail: mail@ieaghg.org
www.ieagreen.org.uk

OVERVIEW

Background to the Study

The IEA Greenhouse Gas R&D Programme (IEA GHG) has recently commissioned the British Geological Society (BGS) to conduct a regional assessment of the Indian subcontinent in order to gauge the potential for CO_2 storage in geological reservoirs in that region. This is the 3rd regional capacity study conducted by the IEA GHG following on from assessments of Europe[1] and North America[2]. It should be noted that the study only assessed the 4 main options of geological storage; deep saline aquifers, depleted oil and gas fields, and storage in deep unminable coal fields. In addition, the study has undertaken an assessment of the current large point source emissions from the power sector on the Indian subcontinent and assessed their geographical relationship with possible geological stores. This process is also known as source-store matching, and a good source of CO_2 close to suitable geological storage reservoirs can significantly impact on the costs and technical feasibility of a CCS operation. Without nearby sources for injection, the transport element of the CO_2 chain becomes more expensive, and thus can result in the classification of a proposal as uneconomical.

The choice of the Indian subcontinent for this third study is primarily down to 2 main reasons. Firstly, as an emergent economy, India is considered likely to experience high growth in energy demand due to increasing economic development, and this will naturally include a corresponding increase in anthropogenic CO_2 emissions. Much of the increased power demand will come from increased use of fossil fuels and in particular coal. The growth in energy demand is likely to be met by government backed plans to install increased capacity in power plants throughout many regions. History has taught us that when a country undergoes rapid economic growth, there is a corresponding increase in the demand for power and subsequent increase in anthropogenic CO_2 emissions. The second driver behind the choice the Indian subcontinent is the current lack of any other definitive study into the capacity for CCS in the area.

Scope of Study

One of the first tasks completed for the study was the compilation of inventories of CO_2 emissions from large point sources (>100,000kt CO_2/y) throughout the subcontinent, and these were then entered into the IEA GHG CO_2 Emissions Database. This provided a valuable update to the database, further enabling it as an insightful source of information to the IEA GHG team and its member countries. Once this information was compiled and entered onto the database, it was then combined with a GIS system, allowing the point sources to be mapped onto the geographical map of the Indian subcontinent. The locations and extent of the known oil and gas reservoirs, coal beds, and saline aquifer bearing rock formations were overlaid onto the GIS to highlight any areas with close matching of source to sinks. At this point, the areas that were found to have large basalt formations were also identified and plotted, although they were to take no further part in the study. The decision to exclude storage in basalt formations was taken due to the relatively un-developed science of storage in these formations. It was felt that the technologies used in these processes are not sufficiently technologically advanced to be considered as a sound and secure storage reservoir at present.

---

[1] IEA Greenhouse Gas R&D Programme report no. 2005/2 Building the cost curves for CO_2 storage, Europe, February 2005

[2]; IEA Greenhouse Gas R&D Programme report no. 2005/3 Building the cost curves for CO_2 storage, North America, March 2005

However, it should be noted that these basalt formations are relatively extensive in the Indian subcontinent, and pending the development and advancement of technological options, the potential for storage in basalt formations could be of a significantly large scale. There is also a good correlation between the basalt formations and many of the large point sources, which will prove beneficial and cost effective if large scale storage in basalts becomes technically feasible. Comment on the future potential for basalt storage in India has been made in the report.

Due to the large spatial area covered by the subcontinent, the decision was made early on to address the countries involved on an individual basis. This removes issues related to national boundaries and political issues from the methodology used to assess storage capacity and matching point sources to storage reservoirs. The study therefore addressed point sources and storage options in India, Pakistan, Bangladesh and Sri Lanka independently. This overview will summarise the main findings and outcomes of the study in these sections to maintain the symmetry with the main report.

Results and Discussion

The results obtained from the study are summarised for each individual country on the Indian subcontinent.

India

Currently, India has annual CO_2 emissions of around 1343 Mt[3] and approximately half of this is from large point sources suitable for CO_2 capture[4]. The main fuel used for energy generation in India is coal. The Indian government is backing an initiative to developing up to 9 Ultra-Mega Power Projects (UMPP) to meet increased energy demand. This development will add approximately 36,000MW of installed capacity, with a corresponding increase in CO_2 emissions of approximately 275Mt a year. This first phase of 9 UMPP's is planned to be operational within 7 – 8 years.

The recoverable coal reserves in India are the fourth largest in the world, and it is expected that both open cast and underground mining will occur in all coal fields to a depth of 600m regardless of the quality of the coal reserves. It is also expected that where the reserves are of a superior quality, the reserves are likely to be mined to a depth of around 1200m. By its nature, mining of this magnitude results in fissures and fractures opening in the overburden above the mined seams, and the structural impact of this means that any storage in coal seams would take place at locations that have either not been subjected to selective underground mining, or at depths of 100m below the deepest selective underground mining operations. This is better viewed in a table, see Table 1 overleaf to demonstrate the reserves estimated to be available to CCS in India.

[3] Figure from 2004, United Nations Statistics Division 2007
[4] IEA GHG set a benchmark indicator over which sources are classed as large point sources. This benchmark has been set at 100,000Kt/y. BGS have taken benchmark figure for this report, therefore only sources above 100,000 Kt/y have been included in the IEA GHG emissions database as a large point source for CO_2.

Table 1: Summary of the assumptions made on CO_2 storage capacity of Indian Coal [5]

Depth of coal beds	Coal grade/category	CO_2 storage Capacity
0-300m	All grades of coal	Nil
300-600	Coking Coal Superior grade non coking coal Mixed (Superior: Inferior 1:1) Inferior (E-G) grade Inferior under thick trap	Nil Nil 10% 30% 50%
600-1200	Coking coal Superior non coking coal Mixed grade (1;1 ratio) Inferior grade under trap	Nil Nil 50% 100%

This assessment of coal mining operations results in a theoretical storage potential in deep coal seams of approximately 345Mt across the country. It should also be noted however, that none of the fields that contribute to this value have the potential to store more than 100Mt. CCS involving deep coal seams is still considered as in the demonstration phase, and therefore not suited for full scale deployment, but as more demonstration projects become active around the world, there may be scope for a demonstration project within the Indian subcontinent, to ascertain the relevance of this technology for CCS in India.

Analysis of the oil and gas fields around India resulted in the discovery that many fields are relatively small-scale when considered for the purposes of CCS, and only a few fields have the potential to store the lifetime emissions from even a medium sized coal-fired power plant[6]. Despite this apparent lack of suitably sized reservoirs, recent off shore discoveries of gas reserves could provide opportunities in the future, although this would require further assessment of these newly discovered fields.

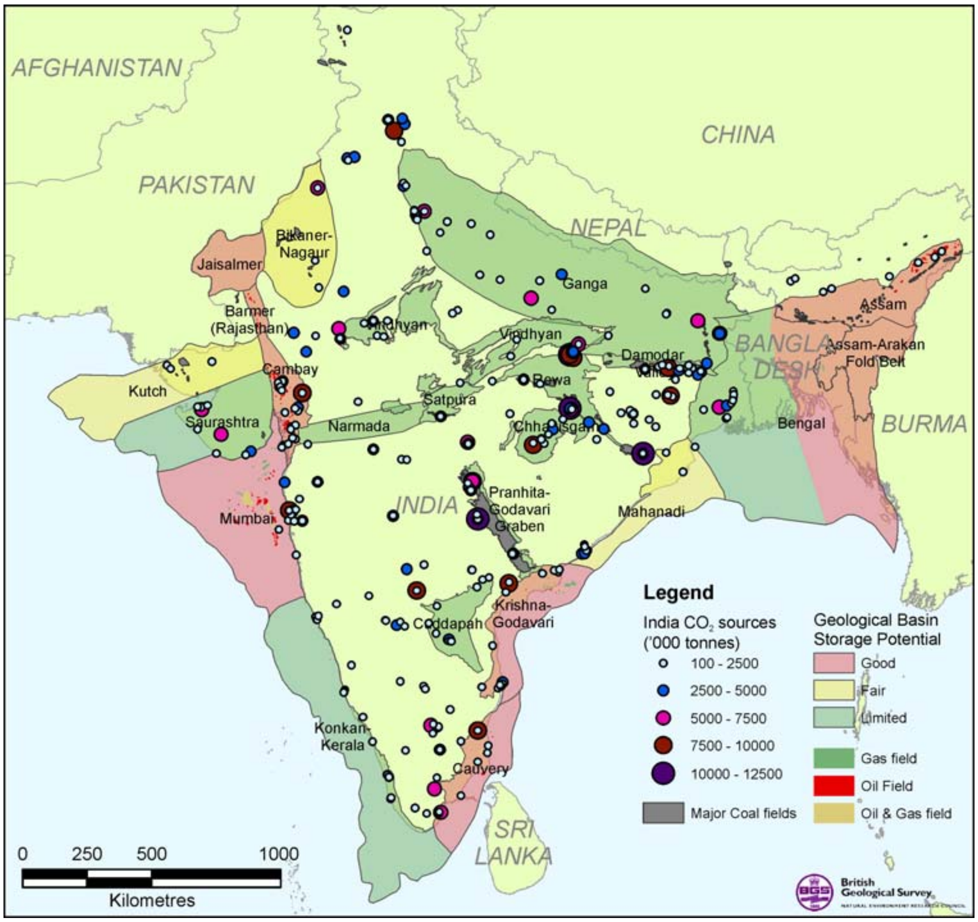
There is potential for CO_2EOR operations, both onshore and offshore, but again this should be explored further on a basin by basin basis in further studies. The extent of the potential for EOR cannot be justified, and a capacity estimate cannot be given without further exploration of the exact size of the oil fields. It has already been pointed out that the exact size of many oil fields isn't included in this report, which is due to limitations of public sector information availability

There is considerable potential capacity for storage in deep saline aquifers around India; although it should be pointed out that the survey of these areas was brief, and by no means definitive. The assessment of storage potential in these formations therefore was subject to certain judgements by the study team, however the survey is clear that there is likely to be substantial potential around the coast and margins of the peninsular. Specifically, there is potential in the shallow offshore areas, in Gujarat and Rajasthan. This can be seen on the map overleaf. The map also clearly shows aquifer storage potential in the areas surrounding Assam, although these reservoirs are approximately 750 - 1000km from 5 large point sources each with emissions greater than 5Mt a

[5] For a greater detail breakdown of this table on a basin by basin basis, see table 2.1.5 on page 36 of the main report.
[6] As the exact size of only a very few oil and gas fields is known, approximations and estimates have been made. For the purposes of this study, and putting this size into context, a medium sized coal-fired power plant is assumed to have lifetime CO_2 emissions of around 100Mt.

year, and therefore storage from these sources may prove costly depending on the transport element and cost of the CCS chain. It should be noted that there are 8 small point sources of up to 2.5Mt annual emissions in the north of the Assam field which could potentially utilise the Assam field to store their CO_2 emissions.

Figure 1: Map showing point sources of CO_2, storage basins and oil and gas fields of the Indian subcontinent



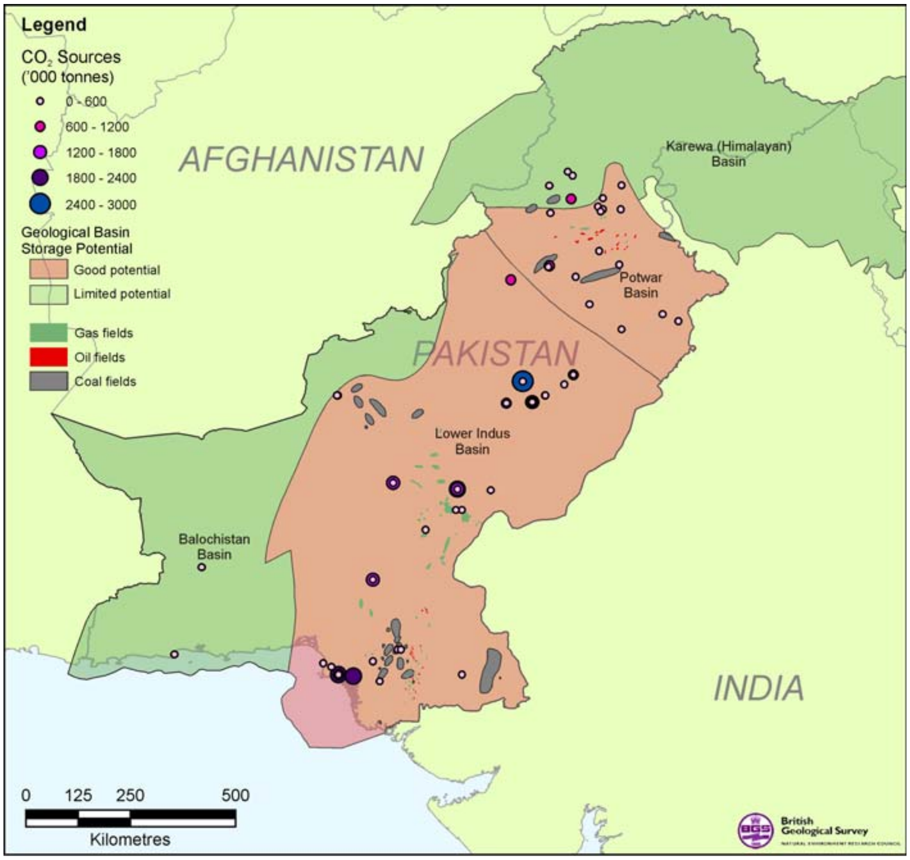
Pakistan

Of Pakistan's annual CO_2 emissions of 125Mt, large point sources make up around 45Mt of this, and 50% of these emissions are from power generation.

Oil fields in Pakistan are relatively small, none having the potential to store more than 10Mt of CO_2. The gas fields are a slightly more attractive prospect, with 13 fields having the potential for storage of more than 10Mt, and 4 having the potential for storage of more than 200Mt. Coal fields in Pakistan are not considered to have any storage potential as, with the exception of 1 field, they are all shallow or subject to mining operations. This lack of storage potential means that Pakistan's best option for CCS is the numerous saline aquifers in the Kohat-Potwar and Indus Basins.

In Pakistan's favour for CCS, is the reasonably good matching of large point sources and sedimentary basins with good potential for saline aquifer storage, see figure 2. The second favourable aspect of CCS in Pakistan is the storage capacity in gas fields; estimated at 1602Mt, resulting in the potential to store over 35 years worth of CO_2 in the gas fields alone. Pakistan, therefore, appears to have great potential for deployment of CCS technology in the near future.

Figure 2: Pakistan sources of CO_2 emissions and potential storage reservoirs



Bangladesh

Bangladesh has relatively small annual CO_2 emissions compared with both India and Pakistan, at around 37Mt. Approximately 17Mt of this comes from large point sources, and over 15Mt of that from power generation.

Bangladesh has no oil fields, but has 14 gas fields with storage potential of greater than 10Mt, and 2 with greater than 200Mt. Coal reserves are small scale in Bangladesh, and are not thought to hold significance for CCS.

However, this lack of suitable oil and coal reserves is not expected to impede the deployment of CCS in Bangladesh due to the estimated storage capacity in gas fields. The potential in gas fields alone is in the order of 65 times the annual emissions from large point sources, therefore, Bangladesh is in a strong position to develop and deploy CCS operations around the gas fields indicated as having large storage potential, as these are predominantly within 200km of the emission sources, and in some cases less than 100km.

Sri Lanka

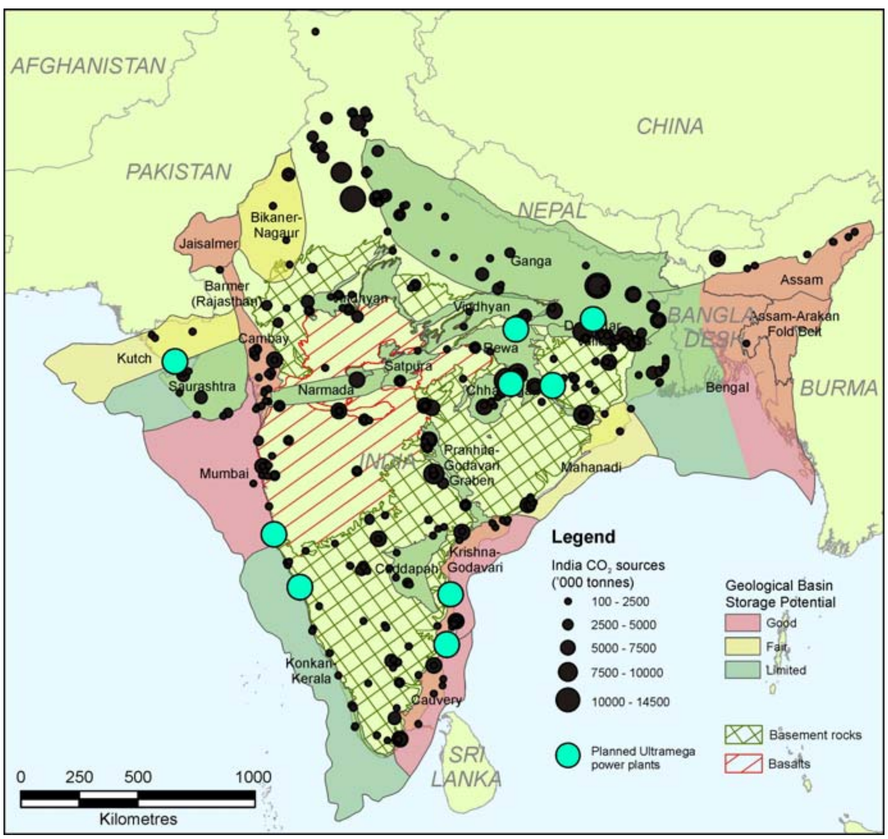
In comparison with the rest of the subcontinent, and indeed many countries, Sri Lanka has relatively small annual CO_2 emissions, at around 12Mt, and only 2.6Mt of this is from large point sources. The main sources for CO_2 emissions on the island are 6 oil-fired power plants, a refinery and a cement plant. This is expected to rise with the installation of a new coal-fired power plant, but relatively speaking in the context of the whole continent, the emissions will still be low.

The geological make-up of Sri Lanka means that the storage potential onshore is non-existent, with no oil, gas or coal fields discovered. The only opportunity for CCS remains offshore to the north-west of the island, involving injection into saline aquifers on the Sri Lankan side of the Cauvery basin. The potential in this basin has been surveyed as good (see Figure 1) and it is conceivable that all the CO_2 emissions from Sri Lanka could be stored here.

Storage in Basalt Formations

Storage in Basalt formations and salt caverns was identified in the study as potentially having a great storage capacity, but due to the classification as an immature technology (IPCC 2005), it was disregarded from this study. Despite this, it can be taken that there are two extremely large areas of India covered by thick basalt formations, namely the Deccan Traps and the Rajmahal Traps. If the concept of storage in basalt formations can be advanced sufficiently to be considered a mature option for CCS, then an assessment of the potential for storage in basalts should be undertaken for the Indian subcontinent. Figure 3 shows the areas of India covered by basalt formations, and there position relative to CO_2 emission sources.

Figure 3. Basalt Formations in India



Expert Review Comments

The draft report was also sent to a panel of expert reviewers, and the comments received back were extremely complimentary. Mostly the comments focussed on typographical inconsistencies, but in addition, comments were made on the need for further work. One suggestion was of a potential follow-on study to determine the potential for CCS on a sub-continent basis and to incorporate the geo-political issues associated with this. This would be analogous to the Regional Partnerships programme in the US, and in particular the PCOR partnership which is working with international factors and cross-national boundaries.

Conclusions

The study has identified the most likely options for CCS throughout the Indian subcontinent, and this should form the basis for further investigation on a more localised scale, and will likely benefit any organisation or body looking to set up a demonstration project.

It is clear that there is potential for CCS to play an important part of the ongoing development of the Indian subcontinent, and that varying options are best suited to different areas. The geographical range of the study area means that some basins with good potential for storage are located several hundred kilometres from large point sources, in particular the point sources in the north and centre of the subcontinent are between 500 and 1000km from basins and reservoirs with good storage potential. The coastal areas show the greatest potential for successful deployment of CCS technologies, with good offshore potential for storage in the Mumbai, Krishna-Godavari and Cauvery basins.

Pending development of technological options, there could be potential for large scale storage in Basalt formations in India.

Recommendations

A follow-on study considering the geo-political issues relating to storage on a sub continental basis could be considered.

A more detailed assessment of the storage capacity in oil fields in India could be considered as cuurently relatively little is known regarding their potential for CO_2EOR, and whether or not it has the potential to play a part in the mix of CCS options for the area.

Although the total capacity for storage in deep unminable coal seams is not high, the proximity of several large point sources of CO_2 to the major coal fields in the Pranhita-Godavari Graben region, which are otherwise 500km from the nearest potential sedimentary storage basin, could theoretically provide a niche opportunity for CO_2ECBM. As CO_2ECBM is still considered as an emerging CCS technology, the development of numerous demonstration projects around the world could contribute to the establishment of a demonstration project in this region of India. A feasibility study could be of use to determine the likely potential of such a project.

There could be some benefit in undertaking a study into the storage potential in basalt formations in India in the future, once the technology has been demonstrated.

A regional assessment of the potential for CO_2 storage in the Indian subcontinent

Sustainable and Renewable Energy Programme

Commissioned Report CR/07/198

BRITISH GEOLOGICAL SURVEY

SUSTAINABLE AND RENEWABLE ENERGY PROGRAMME

COMMISSIONED REPORT CR/07/198

A regional assessment of the potential for CO_2 storage in the Indian subcontinent

The National Grid and other Ordnance Survey data are used with the permission of the Controller of Her Majesty's Stationery Office.
Licence No: 100017897/ 2008.

S. Holloway, A. Garg, M. Kapshe, A.S. Pracha, S.R. Khan, M.A. Mahmood, T. N. Singh, K.L. Kirk, L.R. Applequist, A. Deshpande, D.J. Evans, Y. Garg, C.J. Vincent and J.D.O. Williams

Keywords

Report; keywords.

Bibliographical reference

HOLLOWAY, S., GARG, A., KAPSHE, M., PRACHA, A.S., MAHMOOD, M., APPLEQUIST, L.R., DESHPANDE, A., EVANS, D.J., GARG, Y., GUPTA, A., GUPTA, G., JOSHI, B., KIRK, K.L., VINCENT, C.J. AND WILLIAMS, J.D.O.. 2008. A regional assessment of the potential for CO2 storage in the Indian subcontinent. *British Geological Survey Commissioned Report*, CR/07/198. 190pp.

Keyworth, Nottingham British Geological Survey 2008

BRITISH GEOLOGICAL SURVEY

The full range of our publications is available from BGS shops at Nottingham, Edinburgh, London and Cardiff (Welsh publications only) see contact details below or shop online at www.geologyshop.com

The London Information Office also maintains a reference collection of BGS publications, including maps, for consultation.

We publish an annual catalogue of our maps and other publications; this catalogue is available online or from any of the BGS shops.

The British Geological Survey carries out the geological survey of Great Britain and Northern Ireland (the latter as an agency service for the government of Northern Ireland), and of the surrounding continental shelf, as well as basic research projects. It also undertakes programmes of technical aid in geology in developing countries.

The British Geological Survey is a component body of the Natural Environment Research Council.

British Geological Survey offices

BGS Central Enquiries Desk
Tel 0115 936 3143 Fax 0115 936 3276
email enquires@bgs.ac.uk

Kingsley Dunham Centre, Keyworth, Nottingham NG12 5GG
Tel 0115 936 3241 Fax 0115 936 3488
email sales@bgs.ac.uk

Murchison House, West Mains Road, Edinburgh EH9 3LA
Tel 0131 667 1000 Fax 0131 668 2683
email scotsales@bgs.ac.uk

London Information Office at the Natural History Museum (Earth Galleries), Exhibition Road, South Kensington, London SW7 2DE
Tel 020 7589 4090 Fax 020 7584 8270
Tel 020 7942 5344/45 email bgslondon@bgs.ac.uk

Columbus House, Greenmeadow Springs, Tongwynlais, Cardiff CF15 7NE
Tel 029 2052 1962 Fax 029 2052 1963

Forde House, Park Five Business Centre, Harrier Way, Sowton EX2 7HU
Tel 01392 445271 Fax 01392 445371

Maclean Building, Crowmarsh Gifford, Wallingford OX10 8BB
Tel 01491 838800 Fax 01491 692345

Geological Survey of Northern Ireland, Colby House, Stranmillis Court, Belfast BT9 5BF
Tel 028 9038 8462 Fax 028 9038 8461
www.bgs.ac.uk/gsni/

Parent Body

Natural Environment Research Council, Polaris House, North Star Avenue, Swindon SN2 1EU
Tel 01793 411500 Fax 01793 411501
www.nerc.ac.uk

Website www.bgs.ac.uk
Shop online at www.geologyshop.com

Foreword

This report is the published product of a study by the British Geological Survey (BGS), the UNEP Risoe Centre, Denmark, the Maulana Azad National Institute of Technology (Bhopal, India), the Sustainable Development Policy Institute (Islamabad, Pakistan), Dr T.N. Singh (India) and Mr M.A. Mahmood (Bangladesh), commissioned by the IEAGHG R&D Programme and DEFRA under contract number IEA/CON/06/127. It consists of an analysis of the major industrial sources of CO_2, the geological CO_2 storage potential, and flow sheets for the analysis of the potential costs for carbon dioxide capture and storage in India, Pakistan, Bangladesh and Sri Lanka. The latter are presented with a view to constructing marginal CO_2 abatement cost curves for India, Pakistan and Bangladesh in the future.

An accompanying GIS, in ArcGIS 9.1 format, is available from the IEAGHG R&D Programme.

All the maps in this report are intended to provide a graphical example for accompanying textual material. International boundaries of different countries are shown only for information and display purposes. These boundaries are neither authentic nor correct.

Acknowledgements

The authors gratefully acknowledge the help of the IEAGHG project manager, John Gale, and the DEFRA project manager, Dr Matthew Webb. We would also like to thank the US Geological Survey (USGS) and Petroleum Economist Ltd., who have generously freely provided data for the GIS and final report. We would particularly like to thank Dr A.J. Kumar Singh of the Central Mining Research Institute for the support he provided to the project during its early stages.

S. Holloway, D.J. Evans, K.L. Kirk, C.J. Vincent and J.D.O. Williams publish with permission of the Executive Director, British Geological Survey (NERC). They would like to thank Dr G.A. Kirby and Dr N.J. Riley, who reviewed the draft report.

Contents

FIGURES

TABLES

Summary

This project:

- Updates the IEAGHG R&D programme CO_2 sources database with all the major current and planned industrial sources of CO_2 in India, Pakistan and Bangladesh (the updated CO_2 sources database is available from the IEAGHG R&D Programme).
- Identifies the CO_2 storage capacity of each of these three countries in oil and gas fields and coal seams and ranks the sedimentary basins in India, Pakistan, Bangladesh and Sri Lanka in terms of their saline aquifer CO_2 storage potential (sedimentary basins north of the frontal thrusts of the Himalayas were not investigated).
- Identifies the local costs of the main elements of the CO_2 capture and storage chain, such that they could be used to produce marginal CO_2 abatement cost curves in a future project.
- Provides a geological CO_2 storage potential GIS of India, Pakistan, Bangladesh and Sri Lanka.

Current CO_2 emissions from large point sources in India, Pakistan, Bangladesh and Sri Lanka compared to the most recent estimates of total national CO_2 emissions are shown in Table 0.1.

Table 0.1 Current CO_2 emissions from large point sources in India, Pakistan, Bangladesh and Sri Lanka.

Country	Annual CO_2 emissions from large point sources (10^6 tonnes)	Total annual CO_2 emissions 2004 (10^6 tonnes)*
India	721	1343
Pakistan	45	126
Bangladesh	17	37
Sri Lanka	3	12

* 2004 is the latest year for which information is available. Source: United Nations Statistical Division 2007

All four countries are undergoing rapid economic development and under a business-as-usual scenario there will be a parallel increase in CO_2 emissions. This is well illustrated by a comparison of CO_2 emissions from operational power plants in India with those under construction or planned. Under the Eleventh 5-year Plan (2007-2012) India is in the process of installing nearly 58 GW of generating capacity. Additionally, India is planning to build up to nine ultra-supercritical coal-fired power plants each of up to 4 GWe installed capacity. These Ultra-Mega Power Projects (UMPPs) alone could add a further 257 Mt CO_2 to India's emissions within the next 7-8 years. (Table 0.2).

Table 0.2 Comparison of annual CO_2 emissions from operational power plants in India with those planned and under construction (million tonnes CO_2)

Operational power plants	467.36
Planned or under construction power plants (11th plan)	395.77
Planned Ultra Mega Power Projects	257.34

This indicates that India's emissions from the power sector alone will likely more than double over the next decade.

India's annual CO_2 emissions from existing and operational large point sources were 720.99 Mt CO_2 in 2005-6. Figure 0.1 shows that the main potential CO_2 storage sites in India are located around the margins of the peninsula and in Gujarat and Rajasthan. Thus CO_2 sources in the centre of the peninsula are poorly placed with respect to potential CO_2 storage sites.

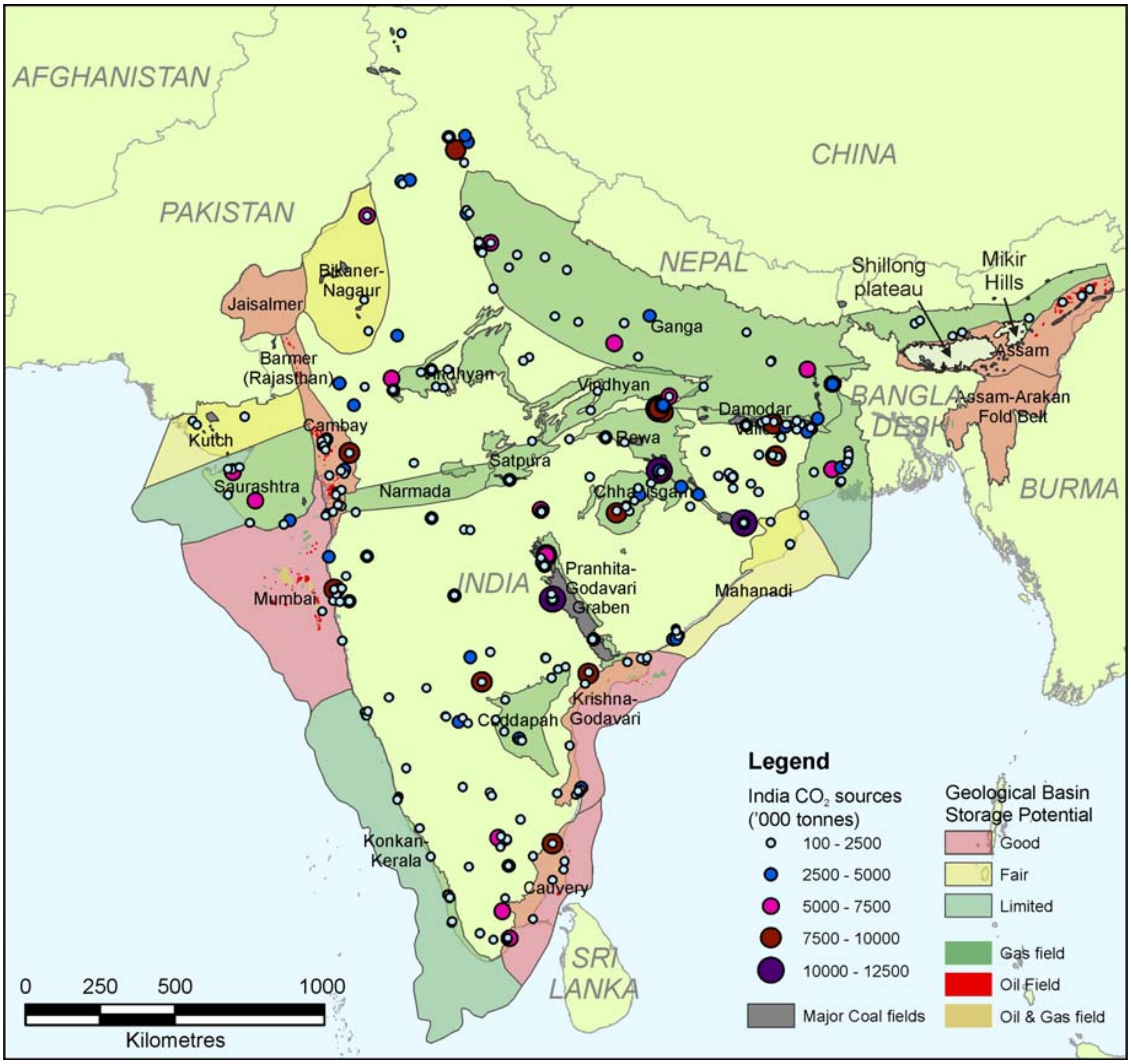


Figure 0.1 Location of CO_2 point sources and CO_2 storage potential in India (basin outlines mainly after DGH)

The brief survey of the CO_2 storage potential of India's sedimentary basins made in this report is far from definitive and their classification into basins with good, fair and limited saline aquifer CO_2 storage potential inevitably involved judgements, in some cases made on very slender evidence. Nevertheless, it is clear that there is likely to be considerable saline aquifer CO_2 storage potential around the margins of peninsula India, especially in the shallow offshore zone and in Gujarat and Rajasthan. There is also considerable saline aquifer storage potential in Assam and probably in Cachar, Tripura and Mizoram, although this is stranded relative to the main emission sources in India, which are in the peninsula.

There is estimated to be limited storage potential in India's coalfields (345 Mt CO_2), oil fields (1.0 to 1.1 Gt CO_2) and gas fields (2.7 to 3.5 Gt CO_2). Even if all this capacity were to be deployed it would make little impression on future emissions from large point sources, which were about 721 Mt CO_2 in 2005-6.

Pakistan has relatively low annual CO_2 emissions from large point sources (45.06 Mt CO_2). It has significant CO_2 storage potential (1.7 Gt CO_2) in its gas fields when they become depleted. Four gas fields (the Sui, Mari, Qadirpur and Uch fields) are estimated to have the potential to store >200 Mt CO_2. Moreover Pakistan has good potential for saline aquifer CO_2 storage in the Lower Indus and Potwar Basins. There is little storage potential in Pakistan's coalfields and oil fields - none of the oil fields are thought to have a storage capacity of 10 Mt or more. Nevertheless it is clear that Pakistan is well placed to exploit CCS technology. All the major CO_2 sources are close to potential gas field storage sites or above sedimentary basins with good saline aquifer CO_2 storage potential (Figure 0.2).

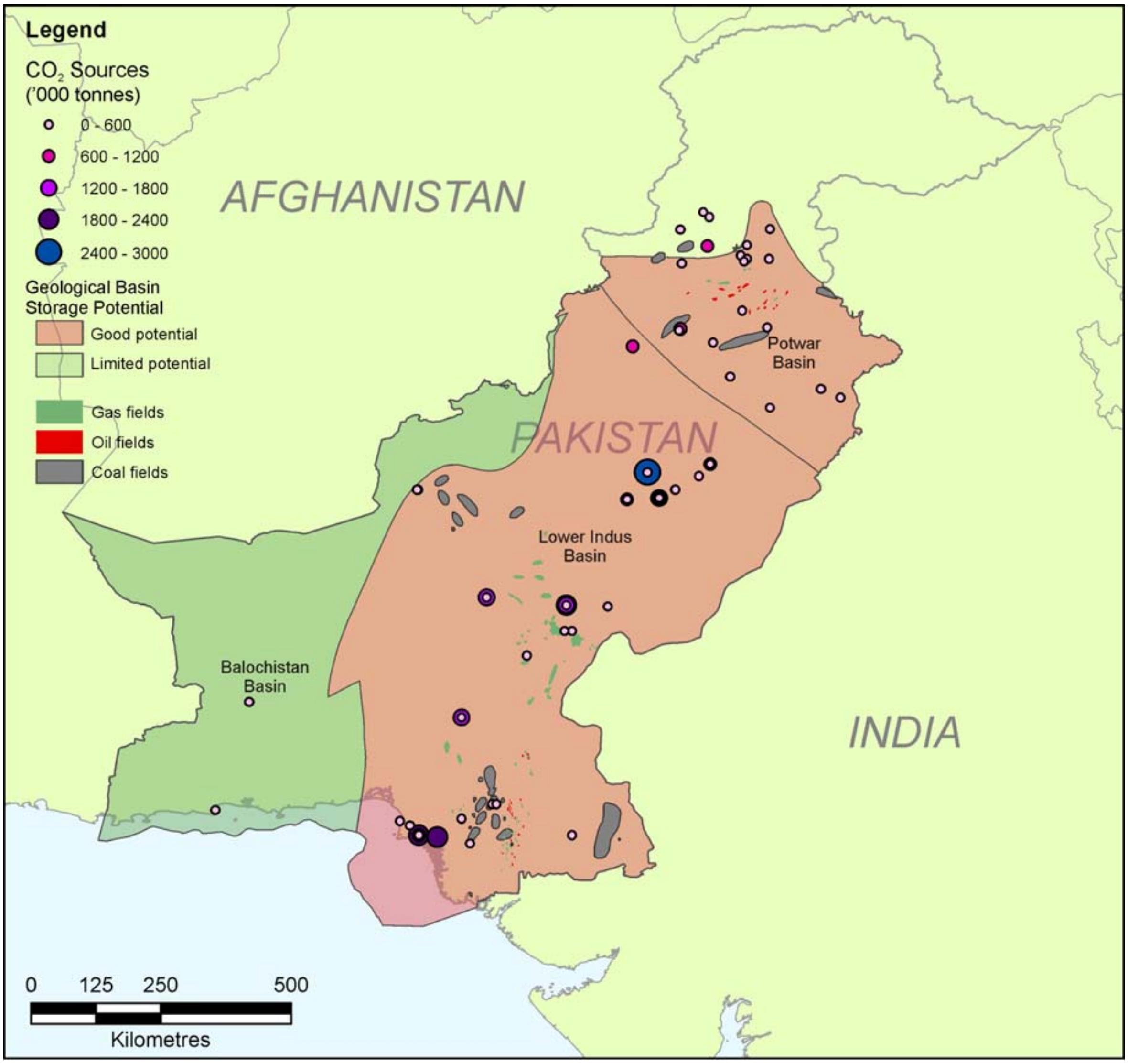


Figure 0.2 Location of CO_2 point sources and potential geological storage sites in Pakistan

Bangladesh has very low annual CO_2 emissions from large point sources (approximately 17 Mt CO_2). These emissions come mainly from power plants and cement factories in the east of the country and the refinery at Chittagong. It is thought to have very significant CO_2 storage potential in its gas fields (1133 Mt CO_2) which will become available gradually as the individual fields are depleted. The small coalfields in the NW of Bangladesh have no significant CO_2 storage potential. Saline aquifer CO_2 storage potential could not be quantified in the current project due to lack of appropriate geological data. Nevertheless it is clear that Bangladesh probably has very significant CO_2 storage potential in saline aquifers in most of the eastern half of the country, both onshore and offshore. Geologically, this aquifer storage capacity is located in the prominent anticlines in the eastern part of the Bengal Basin and likely also in the Chittagong Hill Tracts. Thus, although no significant CO_2 storage capacity has been identified west of the Jamuna River, where the major source is the coal-fired power plant at Barapukuria, Bangladesh is well placed to take advantage of CCS in the future. The locations of point sources, gas fields and areas with good saline aquifer CO_2 storage potential in Bangladesh are shown in Figure 0.3.

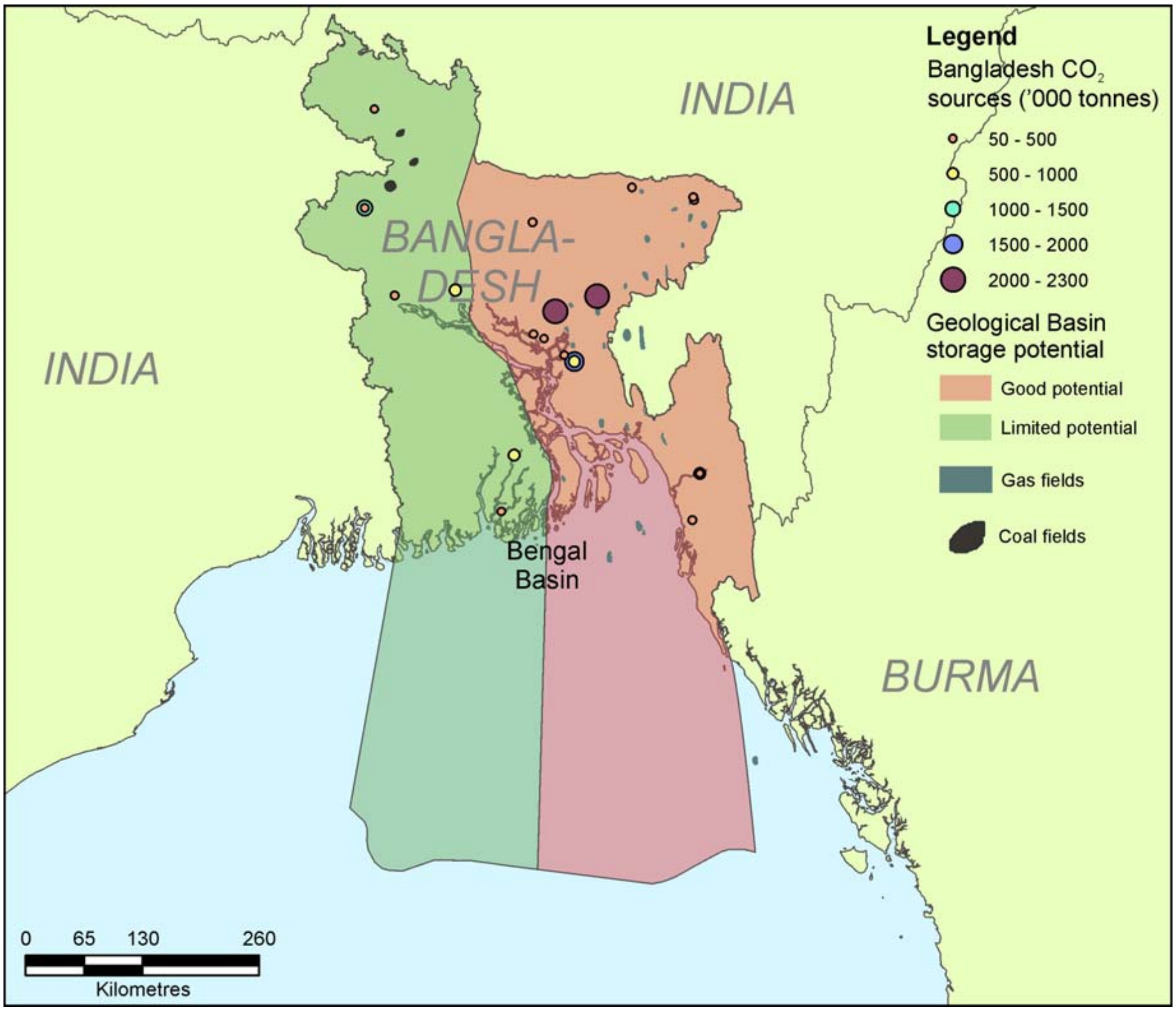


Figure 0.3 Location of CO_2 point sources and potential geological storage sites in Bangladesh

Sri Lanka's total annual emissions of CO_2 from large point sources are comparatively small, and estimated to be approximately 2.6 Mt. These will be increased by the operation of new coal-fired power plant, but national emissions will still be very small in global terms.

Geologically, most of onshore Sri Lanka is made up of Precambrian crystalline rocks with no CO_2 storage potential. There are no coal deposits known in Sri Lanka. No oil fields or gas fields have been discovered to date, but there is oil and gas potential in the Sri Lankan side of the Cauvery Basin, offshore to the north of the island, in Palk Bay and the Gulf of Mannar (Figure 0.4). There may be some saline aquifer CO_2 storage capacity in this area as well, but it cannot be quantified at present. The new coal-fired power plant under construction at Norochcholai is relatively well placed with respect to the inferred CO_2 storage potential in the Cauvery Basin.

There is considerable scope to improve the CO_2 storage capacity estimates in all countries. There is a particular need to firm up and quantify the perceived aquifer CO_2 storage potential in India. Without this, India's geological CO_2 storage potential is perceived to be very limited - unless the basalt storage concept can be matured into a demonstrable solution to large point source emissions. Therefore it is recommended that the following further work could usefully be undertaken:

In India:

- The CO_2 storage capacity of the saline water-bearing reservoir rocks in one or more of the strategically placed sedimentary basins in India considered to have good aquifer storage potential should be quantified. This would require a detailed review of oil and gas exploration data and thus would require input from an organisation holding the necessary data.
- The potential to retrofit India's existing, under construction and planned coal-fired power plants for carbon dioxide capture could be investigated.
- The potential and outline costs for geological storage of the emissions from one or more of India's major planned power plants should be estimated.
- Scientific debate about the saline aquifer CO_2 storage capacity of India's sedimentary basins should be encouraged, in order to establish their true potential.
- The CO_2 storage capacity of India's oil and, particularly, gas fields should be estimated on a field-by-field basis. This would require field-by-field estimates of ultimately recoverable reserves. Such a study could include identification of fields with potential for CO_2 storage and enhanced oil recovery. This could identify potential low-cost pilot projects.

In Pakistan:

- Potential storage sites could be matched with sources of emissions.
- The storage capacity of Pakistan's saline water-bearing reservoir rocks could be quantified
- The CO_2 storage capacity of Pakistan's gas fields could be estimated in more detail and expected close of production dates could be used to estimate when fields might be available for CO_2 storage.
- The potentially for retrofit of Pakistan's fossil fuel-fired power plants for carbon dioxide capture could be investigated.

In Bangladesh:

- Further investigation of the potential to retrofit fossil fuel fired power plants for CCS could be investigated.

- The CO_2 storage capacity of Bangladesh's gas fields could be estimated in more detail and expected close of production dates could be used to estimate when fields might be available for CO_2 storage.
- The CO_2 storage capacity of Bangladesh's saline water-bearing reservoir rocks could be quantified.

In Sri Lanka:

- Further investigation to more closely determine the CO_2 storage potential of the Sri Lankan side of the Cauvery Basin is considered to be a necessary first step towards determining the national CCS potential.

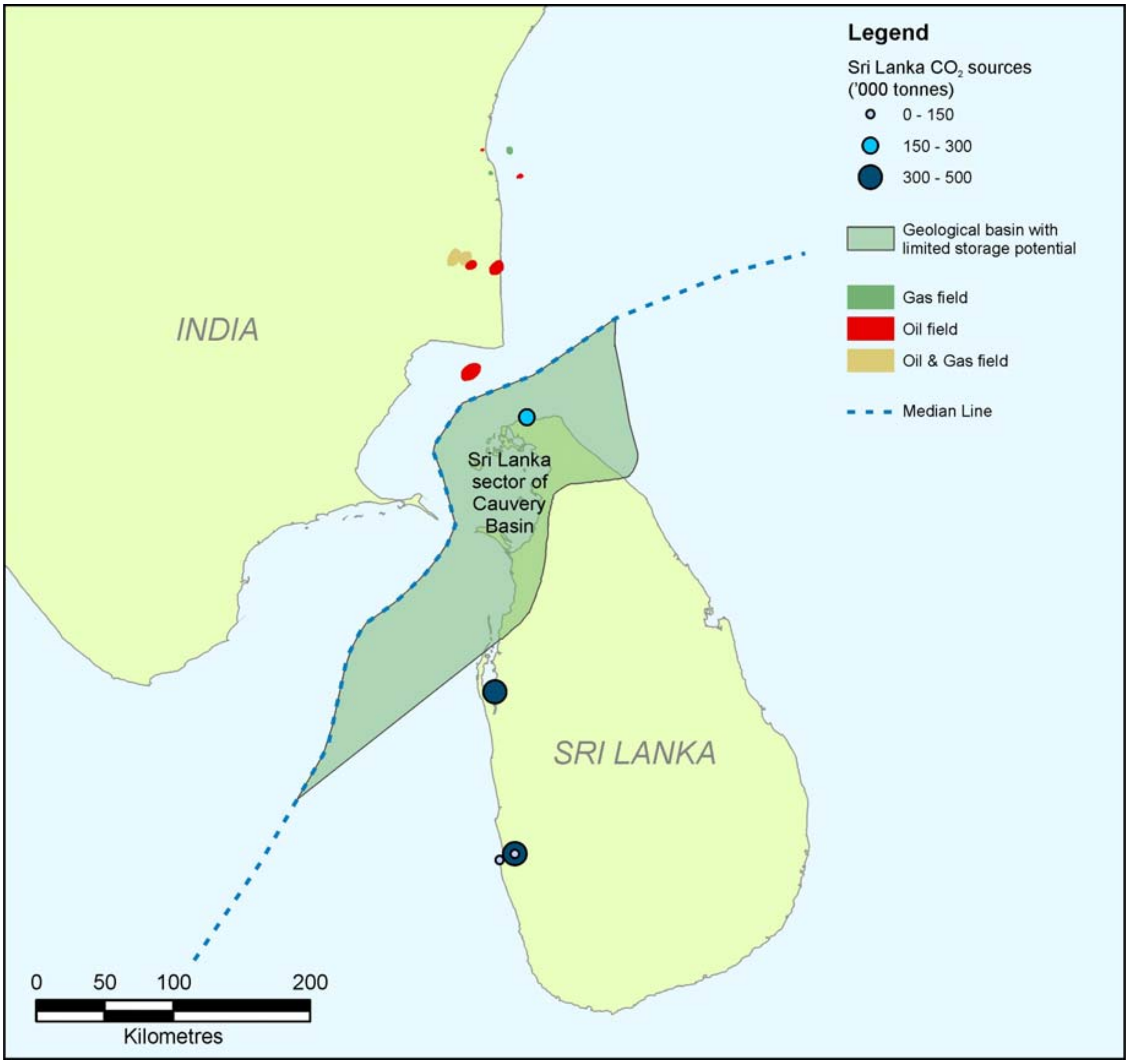


Figure 0.4 Location of CO2 sources in Sri Lanka and the oil and gas fields of the Cauvery Basin

Reference

United Nations Statistics Division 2007. http://unstats.un.org/unsd/environment/air_co2_emissions.htm (accessed January 2007).

1 Introduction

The objectives of this regional assessment of the potential for CO_2 storage in the Indian subcontinent are to:

1. Identify and characterise all the major current and planned large industrial CO_2 sources in India, Pakistan, Bangladesh and Sri Lanka, including those under construction.
2. Update the IEAGHG R&D Programme's CO_2 sources database.
3. Identify and rank sedimentary basins in India, Pakistan, Bangladesh and Sri Lanka in terms of their geological CO_2 storage potential.
4. Identify, where possible, the CO_2 storage capacity in saline water-bearing sedimentary rocks (saline aquifers), oil and gas fields and coal seams.
5. Produce flow sheets identifying the local costs of the main elements of the CO_2 capture and storage chain, such that the information in 1-5 could be combined to produce marginal CO_2 abatement cost curves in a future project.
6. Produce a geological CO_2 storage potential GIS of India, Pakistan, Bangladesh and Sri Lanka, incorporating the information obtained in steps 1-4 above.

These CO_2 sources and storage potential of the four countries are considered individually in the following four chapters.

2 India

2.1 CO_2 SOURCES IN INDIA

2.1.1 Introduction

Indian CO_2 emissions in 2000 were 956 Mt (= million tonnes) CO_2, having grown by 61% during the period 1990-2000 (Garg and Shukla, 2002). Large point sources (LPSs), especially thermal power plants, steel plants, cement plants, fertilizer plants, refineries and petrochemical plants contributed about 64% of all-India CO_2 emissions in 2000. The major contributors were power plants (44.9%), steel plants (9.2%) and cement plants (8%) (Kapshe et al, 2003).

Subsequently, India's total CO_2 emissions grew to 1343 Mt CO_2 in 2004 (United Nations Statistics Division 2007). The current survey indicates that large point sources emit some 721 Mt of CO_2.

The twenty-five largest emitters contributed around 36% of the total all-India CO_2 emissions in 2000 and grew around 10% per annum during the period 1990-2000 (Garg et al, 2004). This indicates that there are important focussed carbon dioxide mitigation opportunities in India.

2.1.2 Data Sources and update of the IEAGHG CO_2 sources database

There is no comprehensive database covering all the categories of large point source emissions in India, and there is a general dearth of plant-level information in the public domain. Therefore many diverse data sources were utilized to compile the emissions information used to update the IEAGHG CO_2 sources database. These mainly comprised published documents of the Government of India, State governments and government organizations and institutions. Helpful information was also available from industry federations and autonomous organizations covering various sectors. The Centre for Monitoring of Indian Economy database was used for company-level and plant-level production and fuel data.

Reliable, precise latitude and longitude data was not available for many plants. Therefore, in some cases it was necessary to locate them at the nearest settlement or to rely on data from unpublished sources for mapping the plant locations. In such cases efforts have been made to verify the data by cross-referencing more than one data source.

2.1.3 Sectors

The following sectors of the IEAGHG R&D Programme CO_2 sources inventory were updated:

- Cement
- Fertilizer / Ammonia
- Iron and steel
- Power
- Refineries

2.1.3.1 CEMENT

In India there are around 54 major players in the cement industry, with a total installed capacity of around 157 million tonnes cement per annum (mtpa) at end March 2006 (ICRA, 2006). Large cement plants accounted for 93% of the total installed capacity in India. There are about 71 cement manufacturing plants scattered all over India which have emissions of 0.1 Mt per year or above. Table 2.1 shows the market share of leading cement producers.

Table 2.1 Market Share of Leading Cement Producers over the years (from ICRA 2006)

Financial Year	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**
The Associated Cement Companies Limited	11.2%	12.2%	12.8%	13.5%	13.0%	12.6%
UltraTech CemCo Ltd.	11.9%	11.1%	10.5%	10.1%	10.1%	9.7%
Gujarat Ambuja Cements Limited	10.6%	8.7%	9.5%	10.1%	11.3%	10.6%
Grasim Industries Limited.	9.2%	10.3%	10.9%	10.9%	10.3%	10.3%
Century Textiles and Industries Limited	5.4%	5.0%	4.8%	4.8%	4.8%	4.7%
Birla Corp Limited	4.2%	4.0%	4.1%	4.1%	3.9%	3.6%
The India Cements Limited	7.3%	5.8%	5.4%	5.4%	5.1%	5.9%
Jaiprakash Industries Limited	2.3%	3.9%	3.8%	3.6%	4.3%	4.5%
Lafarge	3.8%	3.8%	3.4%	3.2%	3.4%	3.2%
Others	34.1%	35.2%	34.8%	34.3%	33.7%	34.8%
Total	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

The Indian cement industry has witnessed substantial reorganisation of capacities during the last couple of years through mergers and acquisitions by multinational cement companies such as Holcim, Holcim Mauritius, Lafarge, Italcementi, and Heidelberg Cement.

The growth in the production and consumption of cement in India is directly related to the growth in the construction industry. GDP in the construction industry grew 12.1% during FY2006, 12.5% during FY2005, and 10.9% during FY2004. This has had a positive impact on cement consumption, which increased 10.1% during FY2006 and 8.1% during FY2005 (ICRA, 2006).

In 1960, around 94% of the cement plants in India used wet process kilns. These kilns have been phased out and at present, more than 95% of the kilns are dry process, 3% are wet, and only about 1% are semi-dry.

For the present study an average emission factor of 1.15 kg of CO_2 per kg of cement has been used. It varies between 1.1 for dry process to 1.2 for wet process (Cleantech). Total estimated CO_2 emissions from cement plants included in the updated IEAGHG CO_2 sources database are 111.02 million tonnes.

2.1.3.2 Fertiliser / Ammonia

Two major types of fertilisers are manufactured in India – phosphatic and nitrogenous. Nitrogenous fertilisers include ammonium sulphate, ammonium chloride, urea, etc. India is the world's largest producer of nitrogenous fertiliser, having around 40 plants. Phosphatic fertilisers include single superphosphate and rock phosphate. Potassic and complex fertiliser (different combinations of NPK) are also produced, in smaller quantities.

Presently, there are 56 large fertilizer plants in the country. Of these, 29 units produce urea, 20 units produce Diammonium Phosphate (DAP) and complex fertilizers and 7 units produce low-analysis straight nitrogenous fertilizers. 9 plants manufacture ammonium sulphate as a by-product. In addition to the above, there are about 71 medium and small-scale units in operation producing Single Superphosphate (SSP) (GOI, 2007). Out of these fertilisers producing plants, only 32 plants have an emission above 0.1 Mt and are included in IEAGHG database. Total estimated CO_2 emissions from fertiliser manufacturing plants included in the updated IEAGHG CO_2 sources database are 13.45 Mt.

The majority of ammonia production in India takes place in fertilizer manufacturing units. There are 18 ammonia manufacturing plants with emissions greater than 0.1Mt CO_2 per year (CMIE, 2005). The total production of these plants for the year 2006 was 10.37 Mt. The emissions have been estimated by using an emission factor of 2.104 kg of CO_2 per kg of ammonia (average value for the natural gas process, see IPCC, 2006). Total estimated CO_2 emissions from ammonia manufacturing plants included in the updated IEAGHG CO_2 sources database are 21.83 Mt.

2.1.3.3 Iron and Steel

India is the 10th largest producer of steel in the world, accounting for 3.2% of world steel production, but per capita consumption of steel in India is amongst the worlds lowest. On the basis of routes of production, the Indian steel industry can be divided into three types of producers:

1. Integrated Producers that convert iron ore into steel. There are three major integrated steel players in India, namely Steel Authority of India Limited (SAIL), Tata Iron and Steel Company Limited (TISCO) and Rashtriya Ispat Nigam Limited (RINL).
2. Mini steel plants (MSPs). These are secondary producers who make steel by melting scrap or sponge iron or a mixture of the two. Essar Steel, Ispat Industries and Lloyds steel are the largest producers of steel through this route.
3. Small producers who use steel from integrated and secondary producers for producing finished goods.

In this report we have concentrated on the integrated steel plants; however, a few major secondary producers have also been included in the database. India has 38 major steel plants that have emissions greater than 0.1 Mt CO_2. The integrated steel units usually use the blast furnace – basic oxygen/open hearth furnace process route for iron and steel production. The secondary producers commonly employ the electric arc furnace process and a large number of smaller units rely on other processes such as the induction furnace process and melting by re-rollers.

Emissions from this sub-sector can be ascribed to three distinct sources: the use of coal as reducing agent in the blast furnace, the production of steel from pig iron and the graphite electrode in the electric arc furnace. The average emissions factor used is 2.16 kg of CO_2 per kg of molten metal for integrated plants and 0.45 kg of CO_2 per kg of molten metal for mini and secondary producers (Biswas et al, 2004; GHG protocol). Total estimated CO_2 emissions from steel plants that are operational or under construction and included in the updated IEAGHG CO_2 sources database are 64.85 million tonnes.

2.1.3.4 Power

Power development in India commenced at the end of nineteenth century with the commissioning of the first 130 kW unit at Sidrapong in Darjeeling in 1897, followed by the first steam-driven power plant rated at 1000 kW two years later at Calcutta in 1899, operated by CESC. Installed power capacity in India has increased from 1362 MW to over 100,000 MW since independence and more than 500,000 villages have been electrified. India is now the world's sixth largest energy consumer, consuming about 3% of the world's total energy per year. Electric power is a critical part of the infrastructure necessary for economic development and for improving the quality of life and it is a matter of concern that the annual per capita consumption of India, at about 350 kWh is among the lowest in the world. Further, people in a large number of villages have no access to electricity.

A range of thermal, hydro, nuclear and renewable power plants are operating in India. Thermal generation constitutes more than 80% of total energy generation in India. The thermal power plants are coal, diesel or gas-based. Coal-based power plants are the backbone of the Indian power sector and will continue to be a major source of electricity generation in the country for the foreseeable future as there is a total coal resource of 255.17 billion tonnes of which nearly 96 billion tonnes are proven reserves. Presently power generation is dominated by the public sector, which has about an 89% share of the total installed capacity. In the pre-independence era the power supply was mainly in the hands of the private sector and was essentially restricted to urban areas.

The emission factors that have been used to estimate CO_2 emissions are 1.02, 0.4 and 0.5 tonnes of CO_2 per kWh for coal, gas and diesel based plants respectively. These emission factors are based on Garg et al. (2002) and Biswas et al. (2004). Full details of all the power plants are given in the updated IEAGHG R&D Programme CO_2 sources database. Table 2.2 presents the CO_2 emissions from operating power sector large point sources in India by State.

Table 2.2 State wise Power Sector LPS CO_2 emissions in India

State	Fuel	Capacity MW	Production GW hr	CO_2(kt)
Andhra Pradesh	Coal	6,553	42,850	43,708
	Diesel	37	274	137
	Gas	1,112	8,158	3,263
	TOTAL	**7,702**	**51,282**	**47,108**
Assam	Coal	330	2,012	2,053
	Gas	189	1,152	460
	TOTAL	**519**	**3,164**	**2,513**
Bihar	Coal	1,380	8,243	8,408
	TOTAL	**1,380**	**8,243**	**8,408**
Chhattisgarh	Coal	3,380	24,854	25,352
	TOTAL	**3,380**	**24,854**	**25,352**
Delhi	Coal	1,103	7,339	7,487
	Gas	612	3,734	1,494
	TOTAL	**1,715**	**11,073**	**8,981**
Goa	Gas	48	358	143
	TOTAL	**48**	**358**	**143**
Gujarat	Coal	4,944	31,012	31,634
	Gas	3,056	19,504	7,802
	TOTAL	**8,000**	**50,517**	**39,436**
Haryana	Coal	1,540	9,389	9,576
	Gas	430	3,162	1,265
	TOTAL	**1,970**	**12,551**	**10,841**
Jammu & Kashmir	Gas	175	1,067	427

	TOTAL	**175**	**1,067**	**427**
Jharkhand	Coal	3,158	14,356	14,643
	Gas	90	332	133
	TOTAL	**3,248**	**14,688**	**14,776**
Karnataka	Coal	1,730	10,901	11,119
	Diesel	209	1,386	693
	Gas	220	1,640	656
	TOTAL	**2,159**	**13,927**	**12,468**
Kerala	Diesel	235	1,430	715
	Gas	366	1,416	567
	TOTAL	**600**	**2,846**	**1,282**
Madhya Pradesh	Coal	4,543	31,953	32,593
	TOTAL	**4,543**	**31,953**	**32,593**
Maharashtra	Coal	8,075	51,473	52,504
	Gas	2,072	13,916	5,566
	TOTAL	**10,147**	**65,389**	**58,070**
Orissa	Coal	3,890	23,617	24,091
	TOTAL	**3,890**	**23,617**	**24,091**
Punjab	Coal	2,120	12,926	13,184
	TOTAL	**2,120**	**12,926**	**13,184**
Rajasthan	Coal	2,295	13,993	14,273
	Gas	413	2,785	1,114
	TOTAL	**2,708**	**16,778**	**15,387**
Tamil Nadu	Coal	5,710	36,717	37,450
	Diesel	412	3,069	1,534
	Gas	713	4,888	1,956
	TOTAL	**6,834**	**44,674**	**40,940**
Uttar Pradesh	Coal	9,722	65,642	66,957
	Gas	1,469	9,575	3,830
	TOTAL	**11,191**	**75,217**	**70,787**
West Bengal	Coal	7,285	39,775	40,569
	TOTAL	**7,285**	**39,775**	**40,569**
INDIA TOTAL		**79,613**	**504,899**	**467,356**

** The above numbers are compiled on the basis of the LPS documented in the database and are not the total sectoral emissions for the states.*

Total emissions from operating power plants are 467.36Mt CO_2 p.a. Total emissions from plants planned or under construction excluding the proposed UMPPs are estimated to be 395.77 Mt CO_2 p.a. and total emissions from the proposed UMPPs are estimated to be 257.34 Mt CO_2 p.a.[1]. Thus the emissions from the planned and under construction plants including the UMPPs are significantly greater than those of the operating plants. This is because Government of India has envisaged capacity addition of 100,000 MW by 2012 to meet its mission of Power to All. Achievement of this target also requires the development of large capacity projects at the national level to meet the requirements of a number of States.

The Ministry of Power, Government of India has launched an initiative for development of coal-based Ultra-Mega Power Projects (UMPPs) in India, each with a capacity of 4,000 MW or above. In first phase, nine sites have been identified by Central Electricity Authority (CEA) in nine States for the proposed UMPPs. These include four pithead sites, one each in Chhattisgarh, Jharkhand, Madhya Pradesh and Orissa, and five coastal sites, one each in Andhra Pradesh, Gujarat, Karnataka, Maharashtra and Tamil Nadu.

Nine wholly owned subsidiaries have been established by Power Finance Corporation Ltd. for taking up developmental work. These are:

1. Sasan Power Limited for pit-head project at Sasan (MP)
2. Akaltara Power Limited for pit-head project at Akaltara (Chhatisgarh)
3. Coastal Gujarat Power Limited for imported coal based project at Mundra (Gujarat)
4. Coastal Karnataka Power Limited for imported coal based project at Tadri (Karnataka)
5. Coastal Maharashtra Mega Power Limited for imported coal based project at Girye (Maharashtra)
6. Coastal Andhra Power Limited for imported coal based project at Krishnapatnam, (Andhra Pradesh)
7. Orissa Integrated Power Limited for pit-head project at Orissa
8. Coastal Tamil Nadu Power Limited for imported coal based project at Cheyyur (Tamil Nadu)
9. Jharkhand Integrated Power Limited for pit-head project near Tilaiya village (Jharkhand)

Ministry of Power is playing the role of a facilitator to coordinate with different agencies. These Ultra Mega Power Projects will add 36,000 MW at nine locations within a span of 7-8 years and help in achievement of the targets for faster capacity addition.

2.1.3.5 Refineries

The Indian refinery sector consists of 21 refineries with CO_2 emissions > 0.1 Mt. Total installed refinery capacity of the country stood at 127.36 Mtpa at the end of April 2005, increasing marginally by 1.4 Mt from 2003-04 (MoPNG 2005). The total crude oil processed in the country in 2004/05 was 127.117 Mt, which translates into a capacity utilization of 99.80%. However, there were significant differences among the refineries. On one hand, IOC Guwahati, Digboi, Panipat; HPCL (Hindustan Petroleum Corporation Ltd) refineries, BPCL (Bharat Petroleum Corporation Ltd) refinery, ONGC refinery, and MRPL (Mangalore Refinery and Petrochemicals Ltd) ran at more than 100% capacity utilization, and on the other hand, refineries such as IOC Mathura, and both the CPCL (Chennai Petroleum Corporation Ltd) refineries ran at low capacity utilization, and the utilization levels were lowest at the NRL (Numaligarh Refinery Ltd) refinery at Numaligarh - at around 68.07% (TEDDY, 2005). The capacity in 2006 has increased to 141.62 Mtpa.

The public sector share of total refinery capacity stood at 74.09% in 2003-04.

[1] Future emissions forecasts are made on the same basis as estimates of current emissions, i.e. using the data in the IEAGHG R&D Programme CO_2 sources database.

An emission factor of 0.219 Kg CO_2 per kg of product (IEA GHG Database, 2004) was to estimate the CO_2 emission. Total estimated CO_2 emissions from operating refineries included in the updated IEAGHG CO_2 sources database are 30.7 Mt.

2.1.4 Agglomerations of Large Point Sources

LPS clusters observed in the present study closely correspond to the major industrial regions of Sharma and Coutinho (1992):

1. The Hooghly Belt
2. The Mumbai -Pune Belt
3. The Ahmedabad-Vadodara Region
4. The Chennai-Coimbatore-Bengaluru Region
5. The Chotanagpur Plateau Region, and
6. The Mathura-Delhi-Saharanpur-Ambala Region.

Figure 2.1 shows these clusters.

2.1.4.1 THE HOOGHLY BELT

Stretching along the Hooghly river from Naihati to Budge along the left bank and Tribeni to Nalpur along the right bank, the Hooghly Belt constitutes one of the most important industrial regions of India: Jute textiles, engineering, cotton textiles, chemicals, leather footwear, paper and match works are the important industries in the area. The port facilities of Kolkata, proximity to coal, jute and leather-producing areas, cheap transport, availability of large quantities of fresh water and affluent discharge facilities have attracted the industries to this area.

2.1.4.2 MUMBAI-PUNE BELT

Including Bombay, Kurla, Ghatkopar, Vile Parle, Jogeshwari, Andheri, Thana, Bhandup, Kalyan, Pimpri, Kirkee, Poona and Hadapsar, this belt has a heavy concentration of cotton textile, engineering, oil refineries, fertilizer and chemical industries. The belt is discontinuous in the Sahyadri section between Karjat and Pimpri. Cotton textile industry, the nucleus of industrial growth in the area, began here during the 1950s as a result of Parsee enterprise. Development of hydroelectric power in the Sahyadris later on, availability of raw cotton in Maharashtra and Gujarat and cheap labour from Konkan were the main assets of this area besides the most important factor namely, the port facilities of Bombay

2.1.4.3 THE AHMEDABAD-VADODARA REGION:

This region produces cotton textiles, plastics, fertilizer, chemicals and engineering goods on a large scale. The power problem, a handicap till recently, has been overcome successfully as a result of the completion of a number of projects including Dhuvaran Thermal Power Station, Uttaran Gas Power Station, Ukai Hydro-Electric Project and Tarapur Atomic Power Station.

2.1.4.4 THE CHENNAI-COIMBATORE-BENGALURU REGION

Chennai, Coimbatore and Madurai are leading producers of cotton textiles. A number of engineering and chemical industries also have come up at these and several other places particularly Salem and Tiruchirapalli. Bengaluru has cotton, woollen and silk textiles together with a number of public sector engineering industries. The Mettur, Sivasamudram, Papanasam, Pykara and Sharavati hydroelectric projects supply cheap power.

2.1.4.5 The Chotanagpur Plateau Region

This area covering parts of Bihar and West Bengal produces over 80 per cent of India's coal, substantial quantities of iron ore, manganese, bauxite, mica and limestone. It has, therefore, become a hub of heavy industries. Jamshedpur, Bokaro, Kulti, Burnpur and Durgapur are centres of steel production. Asansol, Dhanbad, Bokaro, Ranchi and Jamshedpur are centres of metallurgical and other heavy industries.

2.1.4.6 The Mathura-Delhi-Saharanpur-Ambala Region

This region has two separate belts running in a north-south direction, between Faridabad and Ambala in Haryana, and Mathura and Saharanpur in Uttar Pradesh. The belts merge into an agglomeration around Delhi which is one of the largest industrial cities in India. It has cotton textile, glass, chemicals and engineering industries; Saharanpur and Yamunanagar have paper mills. Modinagar is a large industrial centre with textile, soap and engineering industries and Modipuram has an automobile tyre producing factory. Ghaziabad is a large centre of agro-industries and Faridabad of engineering industries. Ferozabad is a leading centre of glass works. There are sugar factories situated practically on all major stations along the Deihi-Meerut-Sharanpur railway line. Mathura has a large oil refinery. Besides availability of cheap raw materials like sugarcane, raw cotton, sands and wheat bran, a large market is the main stimulus for the industrial development in the area. Thermal power stations at Faridabad and Harduaganj and Bhakra Nangal and Yamuna Hydro Power Projects supply power to the area.

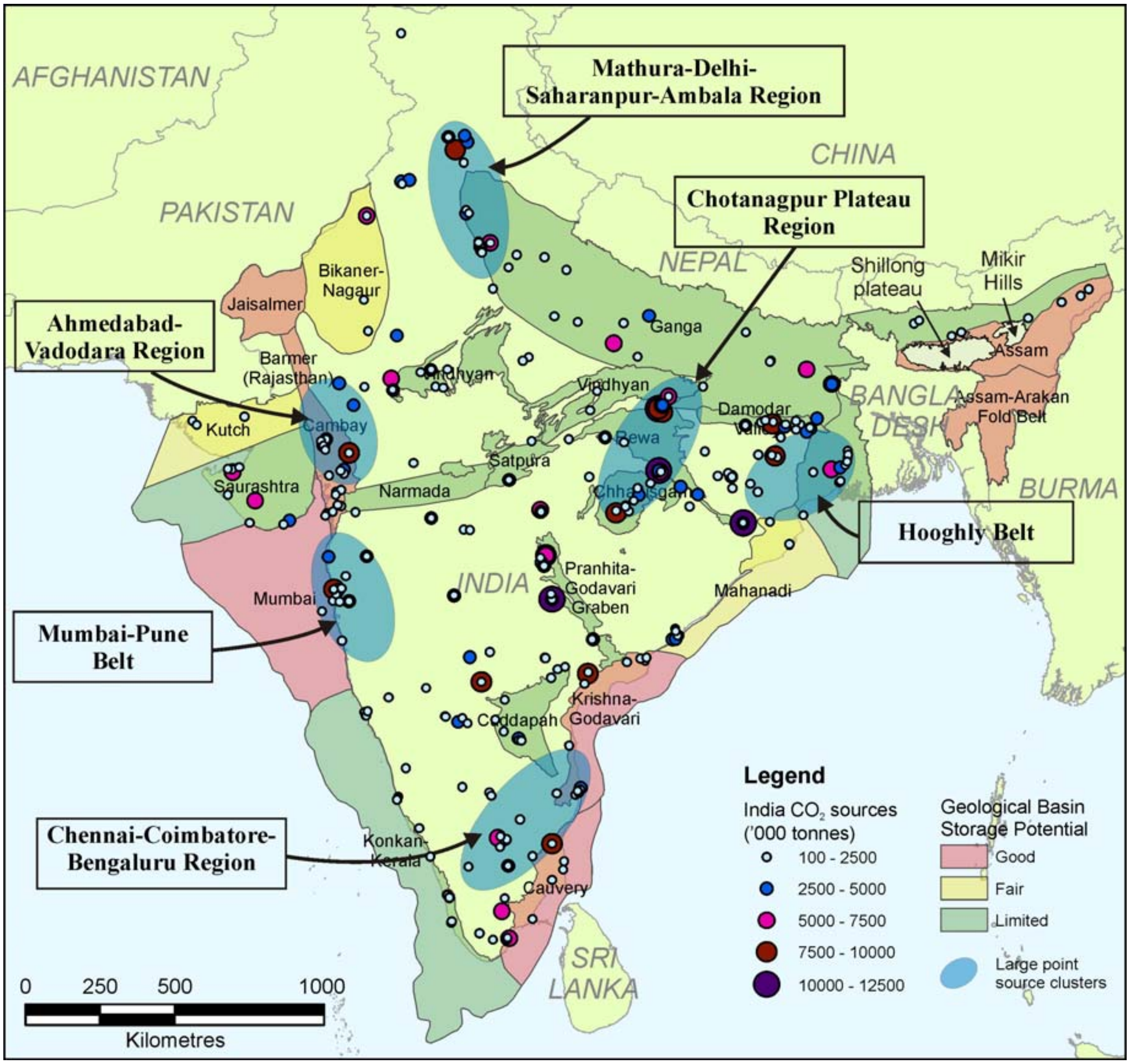


Figure 2.1 Industrial clusters in India

Besides the above regions, a number of smaller clusters with many consumer and other industries and power plants are present, particularly in central India and also around large towns in other parts of the country.

2.1.5 Regions with very few large point sources

India also has some regions of very few LPS like the northern hilly states of Jammu and Kashmir and Himachal Pradesh, the seven hilly northeast states, the west coastal hills and the Thar Desert in the northwest. These are mostly thinly populated regions with low accessibility.

2.1.6 State-wise emissions from various sectors

Figure 2.2 shows the estimated CO_2 emissions for different states. These figures are based on the CO_2 emissions from the LPS for the sectors included in this database only i.e. cement, fertiliser, ammonia, steel, power, and refineries. These numbers do not reflect the total emission from the states.

It can be seen that Uttar Pradesh has the highest CO_2 emission from LPSs, and is followed by Maharashtra, Gujarat and Andhra Pradesh. The high CO_2 emissions in these states are primarily due to thermal power. Gujarat and Andhra Pradesh also have substantial CO_2 emissions from cement sector.

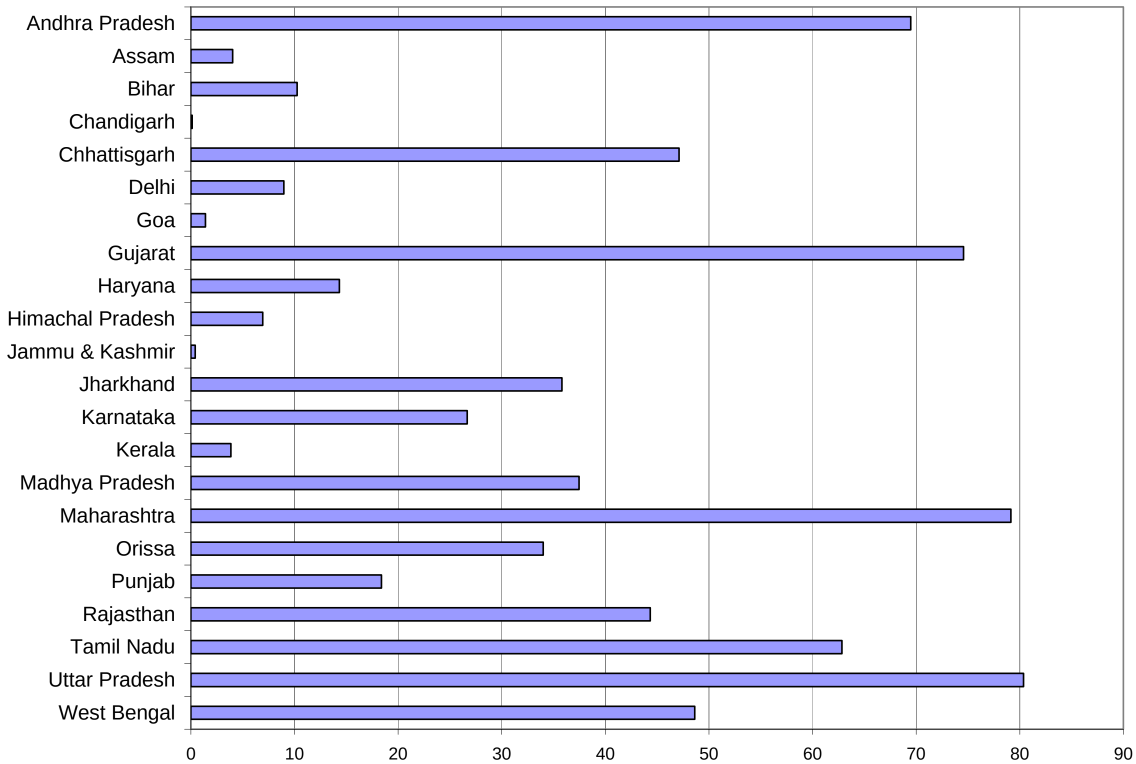


Figure 2.2. Total CO_2 Emissions by State (sources emitting >0.1 Mt per year)

2.2 POTENTIAL GEOLOGICAL CO_2 STORAGE SITES IN INDIA

The potential geological CO_2 storage sites in India considered in detail in this report are divided into three categories:

- oil and gas fields
- coal seams
- saline water-bearing reservoir rocks

The potential for storage in basalt rock formations is not quantified in this report as this storage concept is not considered to be mature at present (IPCC 2005). However, it is noted that two extremely large areas in India are covered by thick basalt formations, the largest of which is known as the Deccan Traps and the smaller as the Rajmahal Traps. If the concept of CO_2 storage in basalt formations can be advanced into a mature option, it may have great potential in India (Singh et al. 2006).

2.2.1 Estimated CO_2 storage capacity in oil and gas fields in India

The methodology used to calculate the CO_2 storage capacity of oil and gas fields is given in Appendix 1.

The location of oil and gas fields in India is shown in Figure 2.3. They occur in three areas: Assam and the Assam-Arakan Fold Belt (NE India), the Krishna-Godavari and Cauvery Basins (SE Indian coast), and the Mumbai/Cambay/Barmer/Jaisalmer basin area (NW India).

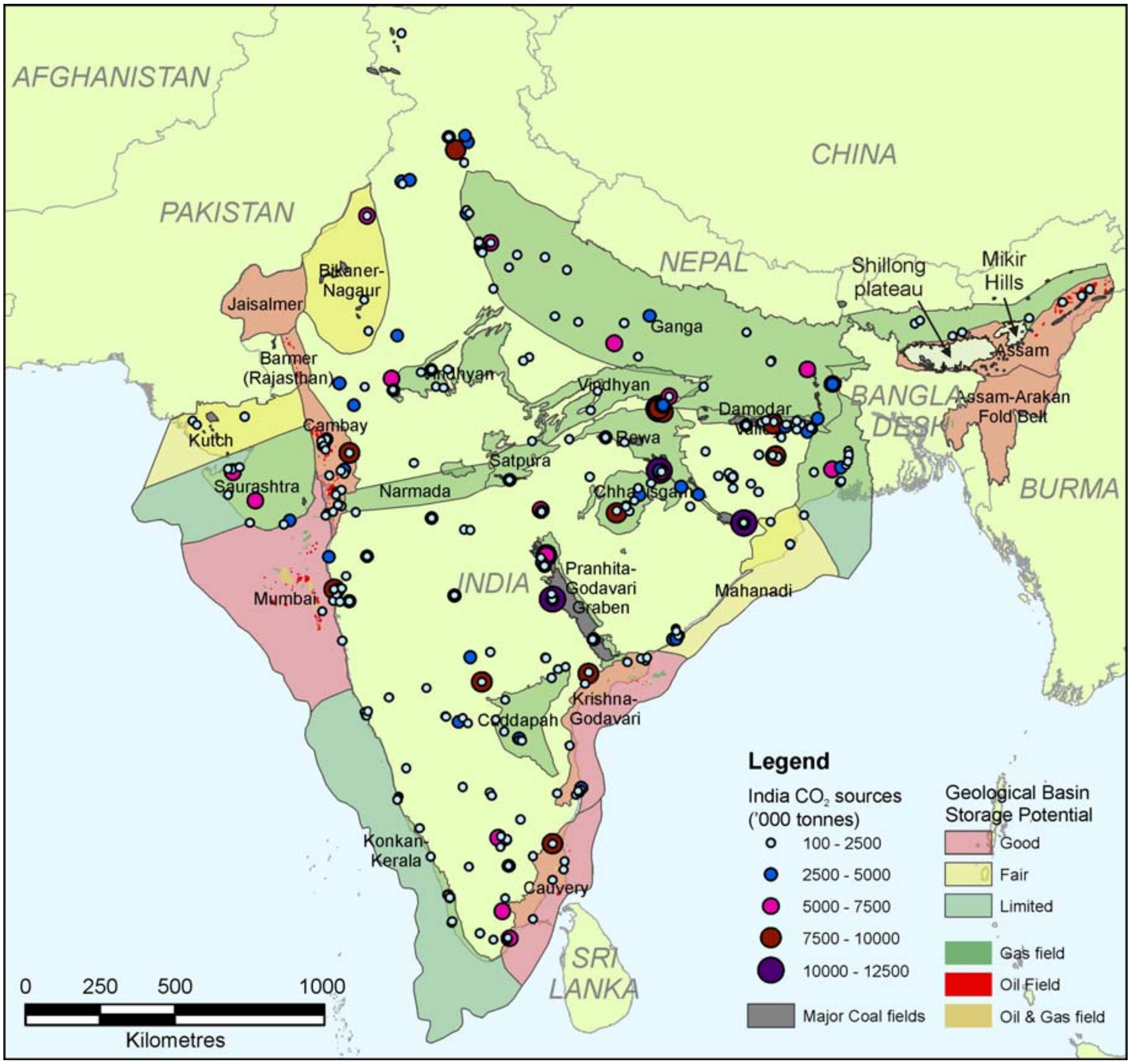


Figure 2.3. Major current CO_2 sources and potential CO_2 storage sites in India.

Initial in-place and ultimate oil and gas reserves in India as of 01/04/2006 are as shown in Table 2.3 (DGH 2006).

Table 2.3 India's oil and gas reserves

Initial in place		Ultimate reserves	
Gas (10^9 cubic metres)	Oil (10^6 tonnes)	Gas (10^9 cubic metres)	Oil (10^6 tonnes)
2664.35	5800.17	1595.68	1652.77

It has been assumed, but not confirmed, that Initial in-place = Oil initially in place, and ultimate reserves = ultimately recoverable reserves as defined in Appendix 1. Based on this assumption, the storage capacity of the oil fields of India is estimated to be 1.0 to 1.1 Gt CO_2, approximately one year's emissions from major point sources. The storage capacity of the gas fields and gas caps on oil fields is estimated to be 2.7 to 3.5 Gt CO_2.

Field-by-field reserve information is not available in the public domain, but some basin-by-basin estimates of oil reserves and thus oil field storage capacity, gleaned from a variety of sources, are given in Table 2.4.

Table 2.4 Estimated CO_2 storage capacity of oil fields in selected basins in India

Basin	*URR Oil mmbbls*	*URR Oil 10^6 tonnes*	*URR Oil 10^6 m^3*	*CO_2 density reservoir conditions (default = 0.6 t m^{-3})*	*FVF (default = 1.2)*	*Estimated CO_2 storage capacity10^6 tonnes*
Assam Basin	2500	333.3	397	0.6	1.2	186
Barmer Basin (Rajasthan)	322	42.9	51	0.6	1.2	24
Cambay Basin	2100	280.0	334	0.6	1.2	156
Mumbai Basin (offshore Mumbai and Gujarat)	6300	840.0	1001	0.6	1.2	469
Total	11222	1496.3	1783			835
India total (DGH 2006)	12395	1652.77	1970	0.6	1.2	1000 – 1100

URR data for Assam from USGS, data for Barmer and Cambay Basins from Cairn Energy, data for Mumbai offshore = USGS – Cairn Energy estimate for Cambay. N.B. data for the productive Krishna-Godavari, Jaisalmer and Cauvery basins is not included.

The reserves of the Mumbai High field are estimated to be approximately 4 billion barrels of oil and 7.4 tcf gas, http://www.hubbertpeak.com/laherrere/GPPI200701.pdf. Production data from the Ankleshwar field (Cambay Basin) suggest that it may have ultimately recoverable reserves of about 400 million barrels of oil.

The figures quoted for CO_2 storage capacity in oil fields are necessarily crude and should be regarded as highly provisional. They do not explicitly include additional potential that might be obtained through enhanced oil recovery (EOR); however, they are possibly overoptimistic in the sense that they are based on the assumption that all the pore space in the field formerly occupied by produced oil and associated gas can be filled by injected CO_2. Any enhanced gas recovery (EGR) resulting from CO_2 injection into depleted gas fields is likely to be marginal in terms of additional storage space as >90% of the gas found in gas fields is commonly recovered in primary production, leaving little scope for EGR.

2.2.2 The coalfields of India

The coalfields of India are described briefly in Appendix 2.

The majority of coalfields in India are of Permian age. Geologically, the vast majority of this Permian coal is located in the Raniganj and Barakar Coal Measures, in the lower part of the Gondwana Supergroup. Nearly 90% of India's total coal resources are in the Barakar Formation.

India also has some resources of lignite and sub-bituminous coal. This is much younger than the Permian hard coals, being of Cainozoic age.

The Gondwana coalfields of India are found in fault-bounded troughs (graben) that overlie either Precambrian igneous and metamorphic basement rocks or Proterozoic sedimentary rocks. The continuity of these troughs has been disturbed by post-depositional folding and faulting such that the coalfields now form a number of separate rather than continuous outcrops within them (shown in grey in Figure 2.4).

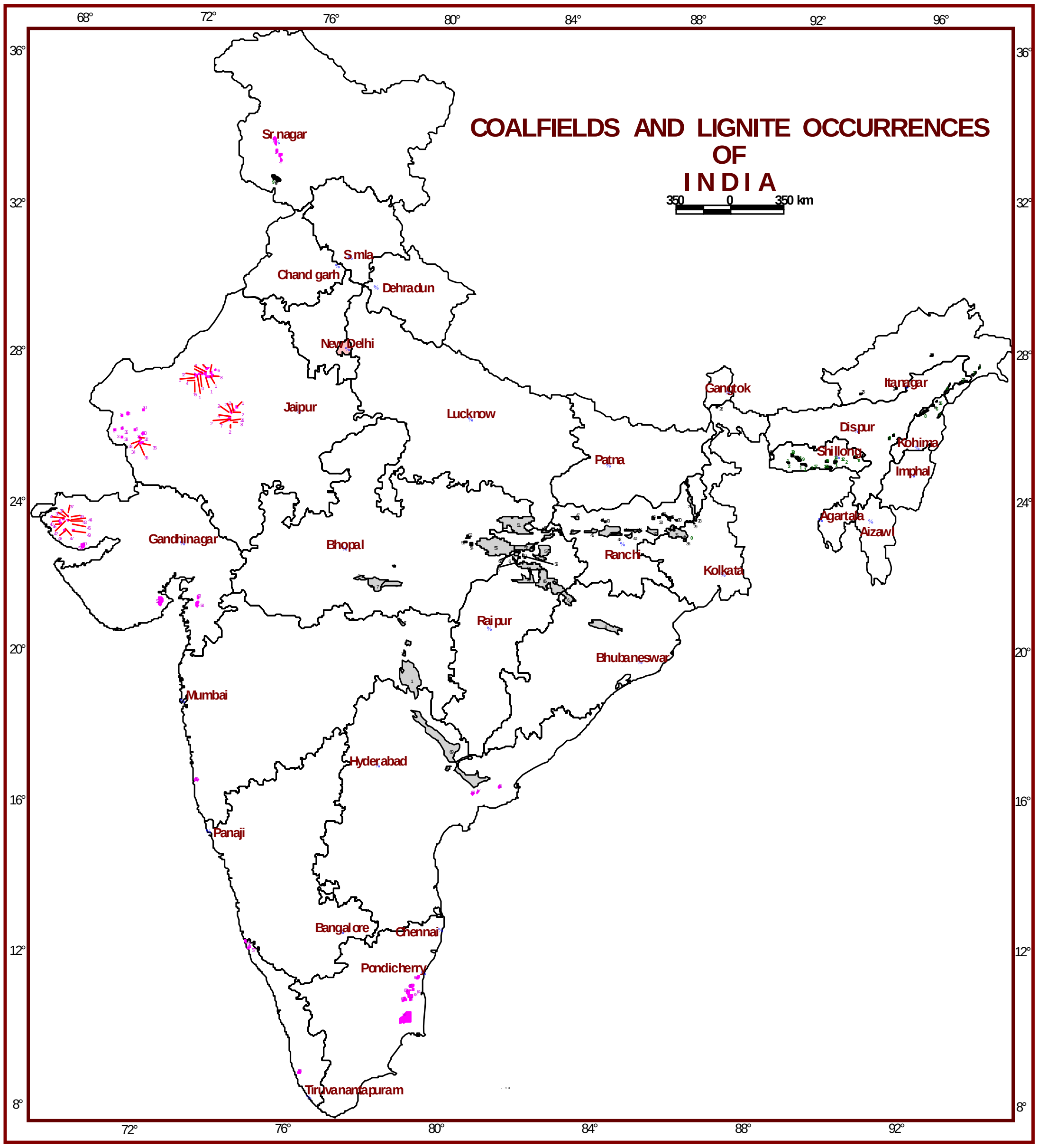


Figure 2.4 Distribution of Gondwana coalfields in India

More than 99% of the bituminous to sub-bituminous coal is found in eastern India, in the states of West Bengal, Jharkhand, Madhya Pradesh, Chhattisgarh, Orissa, Andhra Pradesh and Maharashtra.

2.2.3 Coal resources of India

The data tabulated below is based on the Coal Inventory of India. This is a resource evaluation that covers all known coal seams over 0.5m thickness and down to the depth of 1200m. It was constructed from data made available by the Geological Survey of India, Central Mine Planning and Design Institute, Mineral Exploration Corporation Ltd., Singareni Collieries Co. Ltd and Department of Mining and Geology, Maharashtra. The steps involved in production of the inventory were: regional mapping of major basins, regional exploration of basins considered to have coal-bearing potential and detailed exploration of individual coal-bearing blocks. The resource is categorized by coalfield, State and depth. It is further divided into the following categories: proved (typically explored by boreholes <400 m apart), indicated (typically explored by boreholes 1-2 km apart) or inferred (typically explored by boreholes >1-2 km apart).

A resource evaluation, by State, of coal seams >0.5 m thick at depths <1200 m (GSI 2007) is given in Table 2.5.

Table 2.5 Gondwana coal resources of the States of India as of 1.1.2007

State	Resource estimate as on 1.1.07 under depth:			Total Resource (Mt)
	0-300m	300-600m	600-1200m	
A P	7922	6514	3024	17461
Bihar	160	----	------	160.
Chhattisgarh	32167	8614	669	41450
Jharkhand	36998	14601	3285	54884
**Jharia	-------14213-----------		5217	19430
Maharashtra	6789	2698	183	9670
M.P	12902	6727	148	19777
N E States	787	155		942.
Orissa	44636	16139	1224	61999
U P	1062			1062
W Bengal	12361	10975	4999	28335
Total	**155785**	**80636**	**18749**	**255170**
% share	***61.24***	***31.66***	***7.35***	***100***

** Jharia coalfield resource position is available only in 0-600m depth range and has been included within 300-600m depth account. The reserve position within 300m depth over is found in all the active coalfields except a few hidden pockets under basaltic flow or soil cover.

Coal resources in the inventory are further divided into three categories: proven, indicated and inferred (Table 2.6).

Table 2.6 Geological resources of coal as on 1.1.2007

State	Coal resources in Million tons (Mt)			
	Proved	Indicated	Inferred	Total
Andhra Pradesh	8475	6328	2658	17461
Arunanchal Pradesh	31	40	19	90
Assam	315	27	34	376
Bihar	0	0	160	1 60
Chhattisgarh	9872	27035	4443	41450
Jharkhand	36881	31094	6338	74313
Jharia				
Madhya Pradesh	7584	9259	2934	19777
Maharashtra	4856	2822	1992	9670
Meghalaya	118	41	301	460
Nagaland	4	1	15	20
Orissa	17464	30239	14296	61999
Uttar Pradesh	766	296	0	1062
West Bengal	11454	11810	5071	28335
Total	95920	118992	38260	255172

Cenozoic coals contribute an estimated 946 Mt to the totals in Tables 2.5 and 2.6. They are found in 67 fragmented coal-bearing pockets principally in Assam, Meghalaya, Nagaland and Arunachal Pradesh. Cenozoic coals in general have low ash and high sulphur.

Additionally, a few thin coal seams occur in pockets of Upper Gondwana strata – at Guneri in Gujarat, and Kota and Chikiala in the Satpura and Godavari Valley basins respectively.

Lignite fields are also present. The major fields are given in Table 2.7. Total resources amount to some 25000 Mt but, with the exception of the Neyveli field, a field-by-field breakdown of resources was not available for the study. The Neyveli lignite field produces 24 Mt lignite annually, and feeds three power stations with a combined capacity of 2490 MW.

Table 2.7 Lignite fields of India

Name of lignite field	**State**	**Area km^2**	**Reserves Mt**
Neyveli	Tamil Nadu	1342	2360*
Upper Assam	Assam/Arunachal Pradesh		
Kutch	Gujarat	162	
Patasa	Rajasthan	166	
Total			**25000**

*Proved reserves

2.2.3.1 MAJOR COAL FIELDS OF INDIA

Fields with >500 Mt coal resources are classified as major coalfields (Table 2.8, Figure 2.6).

Table 2.8 Major coalfields of India

Coalfield	Area km^2	Reserve 10^9 tonnes	Coal quality
Auranga	250	3.0	Non coking-Superior
S. Karanpura	195	6.0	Non coking-Superior
N Karanpura	1230	15.9	Medium coking
W Bokaro	259	5.0	Medium coking
E Bokaro	208	7.1	Medium coking
Jharia-Barakar -Mahuda	21058	19.4	Prime and medium coking
Raniganj -Barakar -Raniganj	1530	25.5	Medium coking, Non coking, Superior
Rajmahal	208	14.1	Non coking -Inferior
Singarauli	2202	12.9	Non coking -Inferior
Sohagpur-North -South	3000	4.5	Medium coking Non coking -Superior
Sonhat	850	2.7	Semi coking
Bisrampur	1036	1.5	Non coking -Superior
Hansdeo-Arand	154	5.0	Non coking -Superior
Tatapani-Ramkola	12	2.4	Non coking -Superior
Korba	520	10.1	Non coking-Inferior
Mand Raigarh	500	19.1	Non coking -Inferior
Pench Kanhan	12	2.4	Non coking-Superior
Wardha valley	4130	5.7	Non coking-Superior
Kamptee	95	2.9	Non coking -Superior
Nand Bander		0.8	Non coking –Superior
Godavari valley	17000	17.5	Non coking-mainly superior grade
Talcher	1813	39.6	Non coking –Inferior
Ib River	1375	22.4	Non coking –Inferior

From the surveys undertaken so far, the area of the major coalfields totals nearly 37000 km^2. Of this, approximately 8000 km^2 has been explored in detail, the majority of which contains coal seams at depths of 300-600m. An additional 14500 km^2 has been established as potentially coal-bearing as a result of regional exploration.

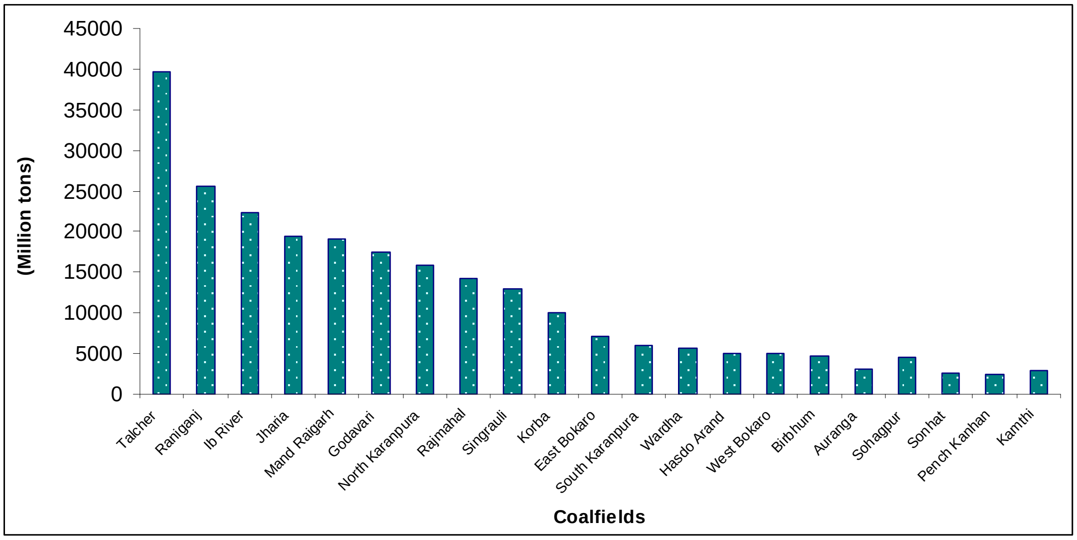


Figure 2.5 Coal resources of the major coalfields of India

2.2.3.2 MINOR COAL FIELDS OF INDIA

Resources of coal in the minor coalfields of India are shown in Table 2.9.

Table 2.9 Minor coalfields of India

State / Coal Field	Coal reserve within		Area-sq.km
	0-300m	300-600m	
W Bengal			
Barjora	114	0	152
Darjeeling	15	0	200
Jharkhand			
Hutar	237	12	-
Daltonganj	144	0	-
Deogarh	400	0	95
Madhya Pradesh			
Johilla	322	0	28
Umaria	181	0	15
Pathakhera	313	134	42
Gurgunda	47	0	-
Mohpani	8	0	-
Jhillimili	267	0	180
Chirimiri	362	0	-
Lakhanpur	451	0	400
Panchbahini	11	0	12
Sendurgarh	279	0	52
Maharashtra			
Umrer	308	0	4
Bokhara	30	0	6
Assam			
Sigrimari	3	0	-
Makum	161	155	-
Dilli Jeypur	54	0	-
Mikir Hills	3	0	-
Arunanchal Pradesh			

Namchik	90	0	-
Meghalaya			
W Darangiri	127	0	-
Balphakram	107	0	-
Siju	125	0	-
Langrin	50	0	12
Mawlong Shella	6	0	-
Khasi Hills	7	0	62
Jaintia Hills	4	0	-
Bapung	34	0	-
Nagaland			
Borjan	10	0	-
Jhanzi Disai	2	0	-
Tuen Sang	1	0	-
Tiru Valley	7	0	-
Total	**4703**	**301**	

2.2.4 Coal quality

Reserves of the various qualities of coal found in India are shown in Tables 2.10 and 2.11.

Table 2.10 Proved, Indicated and Inferred reserves of coking coals in the main coalfields of India (Source: GSI)

State - Coalfield	Type	Proved	Indicated	Inferred	Total
West Bengal - Raniganj	Medium coking Semi coking	210 188	18 432	0 168	228 788
	Sub Total	*398*	*450*	*168*	*1016*
Jharkhand –Jharia, Raniganj, E &W Bokaro, N&S Karanpura	Prime coking Medium coking Semi coking	4614 9451 223	699 10022 472	0 1606 53	5313 21079 748
	Sub Total	*14288*	*11193*	*1659*	*27140*
Madhya Pradesh – Pench Kanhan, Sohagpur	Medium coking	355	1560	273	2188
Chhattisgarh -Sonhat	Semi coking	101	936	0	1037
Totals	**Prime coking**	**4614**	**699**	**-0**	**5313**
	Medium coking	**10016**	**11500**	**1879**	**23395**
	Semi coking	**512**	**1840**	**221**	**2573**
Grand Total	**Coking coal**	**15142**	**14039**	**2100**	**31281**

Table 2.11 Proved and Indicated reserve of superior and inferior grade non-coking coals in the main coalfields of India (as of 1.1.2004, Source: GSI)

State/Coalfield	Superior grade		Inferior grade			Total
	Proved	*Indicated*	*Proved*	*Indicated*	*Inferred*	
W.Bengal						
Raniganj	8856	5871	2015	1483	3758	21983
Jharkhand						
Raniganj	264	143	970	274	31	1684
Jharia	804	159	5398	1691	0	7953
N.Karanpura	412	1048	6348	1436	1610	10854
S Karanpura	1263	863	1279	643	1213	5261
E Bokaro	13	38	85	25	0	167
W Bokaro	60	1	208	12	0	281
Ramgarh	3	13	4	13	5	38
Auranga	0	285	47	2161	503	2997
Rajmahal	48	2844	2030	6923	1284	13128
Bihar						
Rajmahal	0	0	0	0	160	160
Madhya Pradesh						
Pench Kanhan	932	270	336	50	158	1754
Pathakhera	214	13	107	12	103	419
Sohagpur	978	1012	290	230	101	2611
Singrauli	1392	3314	2568	1619	2246	11139
Chhattisgarh						
Sohagpur	92	10	2	0	0	104
Sonhat	111	568	18	649	2	1248
Bisrampur	540	520	61	341	0	1462
Lakhanpur	231	64	135	22	0	451
Hansdo-Arand	283	2011	473	1258	839	4965
Korba	748	378	4233	3697	619	10075
Mand Raigarh	236	3661	836	11339	2461	18533
Tata Pani Ramkola	0	843	0	573	202	1617
Uttar Pradesh						
Singrauli	247	136	519	160	0	1062
Maharashtra						

Wardha Valley	1650	634	1134	489	1437	5344
Kamptee	747	645	487	330	148	2297
Nand Bander	199	25	110	93	20	435
Orissa						
Ib River	199	1672	4718	8275	7472	22356
Talcher	572	3416	9125	17876	7663	38651`
Andhra Pradesh						
Godavari	4138	2920	3953	3172	2514	16697
Total	**26246**	**48166**	**35812**	**66779**	**35409**	**212712**

Limited coking coal is available, mainly within Damodar Valley, in the E &W Bokaro, N & S Karanpura, Raniganj and Jharia coalfields, and a small fraction in Sohagpur and Kanhan Valley coalfields. Very little prime coking coal is available: it is found only in the Jharia coalfield in upper coal seams IX to XVIII - the lower seams have medium- to non-coking properties.

Superior grade non-coking coals of A to D grade with ash and moisture below 34 % are also limited in quantity and available mainly in the Damodar Valley coalfields, with a small fraction of the reserves in Raniganj, South Karanpura and the Central India coalfields.

Inferior grade coal (E to G grade) with ash plus moisture content over 34% is available in the Son Mahanadi Valley, Pranhita Godavari Valley, Wardha Valley, Singarauli, Rajmahal and North Karanpura coalfields. Coal of this grade is primarily used for thermal power generation. Distribution of the different grades of Gondwana coal to 1200m depth is given in Table 2.12.

Table 2.12 Reserves of coal by grade in million tons as of 1.1.2006 (Source: MGMI Indian Mining Directory, 2006)

Type of coal	**Proved**	**Indicated**	**Total**	**% share**
Coking coal				
Prime Coking	4039.	4	4043	1.9
Med. Coking	13692	11765	25457	12.1
Semi coking	482.	1225	1707	0.8
Subtotal Coking	*18213*	*12994*	*31207*	
Non-coking coal				
Grade A	1715	1159	2874	1.1
Grade B	4201	4089	8290	4.0
Grade C	9374	10640	20014	9.6
Grade D	11756	19925	31681	15.2
Grade E +F+G	48166	102591	150757	55.2
Subtotal non coking	*75212*	*138404*	*213616*	
Total	**93425**	**151398**	**244823**	

2.2.5 Undiscovered and deep coal resources

Additional as yet undiscovered coal resources may be present outside the explored areas. Moreover there are areas within the well-delineated coalfields where coal occurs at depths beyond the resource estimation and eventual mining limits. These blocks are of interest because they may be available for underground gasification, coal bed methane production and possibly for carbon dioxide storage – if it proves possible to store CO_2 at these depths. As examples, in the East Bokaro coalfield, approximately 3.2 billion tonnes of coal may be below 1200 m depth. Approximately 6.7 billion tonnes of Barakar coal may be beyond mining depths in the Jharia coalfield, and 0.97 billion tons of mainly of superior quality coal may be below minable depths in the Raniganj coalfield. Coal reserves at depths below 1200 m are expected in the South Karanpura and Sohagpur coalfields.

Additional deep coal resources are also widespread, for example beneath western parts of the Bengal Basin. However these are too deep to be of interest for CO_2 storage in coal at present, although the sandstones in the succession may have potential.

2.2.6 Demand for coal in the Indian market

India's population already exceeds 1 billion and, according to the United Nations, is expected to reach 1.33 billion in 2025 and 1.53 billion in 2050 (World Resources Institute 1998-99). Clearly, India will need electricity, steel, cement, and other industrial products to meet the rising demand. Because of limited indigenous petroleum and natural gas, coal has become the main source of energy.

Indicative future demand for coal (Chaudhary 2000) is summarized as follows in Table 2.13. Demand projection is just indicative because of delay in setting up planned capacity of power stations and other industrial units.

Table 2.13 Indicative annual demand for coal in India (source Chaudhary 2000, numbers rounded)

Consumer	1997	2001	2009-10
Power plants - Power grade	222 Mt	288 Mt	500 Mt
Steel Industry - Coking coal	41 Mt	52 Mt	68 Mt
Cement industry - Superior grade non-coking	18 Mt	21 Mt	37 Mt
Other industry - Superior grade non-coking	41 Mt	51 Mt	85 Mt
Total demand for coal	**323 Mt**	**412 Mt.**	**690 Mt**

Coal-based thermal power plants are spread all over India whereas coal is confined to 8 eastern states. Therefore coal has to be transported over 1000 km to feed some of the remote power stations. The average distance of coal transport to power plants is 675km.

In view of reducing pressure on the railways, environmental protection, control over generation of greenhouse gases and overall economics, there is currently a restriction on transport of low grade coal to remote power plants. The Ministry of Environment and Forest declared that after 1st June, 2001, all coal used more than 1000 km away, or in environmentally sensitive and metropolitan cities power plants, will be washed / processed to an ash content not exceeding 34% (Varma 1999). The restriction clearly demands high production of A to D grade coal or processing of inferior E/G grade coal to reduce ash content to 34%. Obviously, superior grade non-coking coal will be preferred by the remotely located power stations and hence its mining feasibility will improve further in the future.

2.2.7 Estimated CO_2 storage capacity in coal fields in India

Carbon dioxide storage in coal beds is a technology that is only in the demonstration phase (IPCC, 2005), and the evaluation of demonstration projects will affect its perceived applicability and, consequently, the capacity for CO_2 storage in coal beds not only in India but worldwide. The methodology used for estimating the CO_2 storage capacity of coalfields is given in Appendix 1.

A key issue for India's CO_2 storage capacity in coal seams is to what extent mining will take place in each coalfield. It is considered likely that open cast mining and selective underground mining to 600m depth will take place in all major fields irrespective of coal quality, reserve position and distribution pattern, even in basins with only power grade coal. Selective underground mining of superior grade non-coking coal and coking coal is likely to take place down to 1200m in the Jharia, Raniganj, Bokaro, Karanpura and Sohagpur coalfields.

Selective underground mining is likely to lead to the development of fissures and fractures in the overburden above mined seams, and may also enhance the permeability of the Coal Measures below the mined seam. Thus the only areas where CO_2 storage is actually likely to be practical in India are areas of the major coalfields either not subject to selective underground mining or significantly (say 100 m) below mined seams.

Bachu et al. (2007) state that: "Permeability is a determining factor in the viability of a CO_2 storage site, and currently it is considered that coal permeability has to be greater than 1 mD for successful CO_2 injection and/or coalbed methane (CBM) production. Coal permeability is affected by physical (mechanical) and chemical factors. It varies widely and generally decreases with increasing depth as a result of cleat closure with increasing effective stress. The permeability of shallow coals (a few hundred metres deep) is on the order of millidarcies (mD) and higher, while the permeability of deep coals is on the order of microdarcies (μD), which is too low to allow CO_2 injection and flow without fracturing. Coalbed methane cannot be produced if permeability is less than 1 mD (Zuber et al., 1996), and this is generally reached in the depth range 1300-1500 m. It is for this reason that most of the coalbed methane producing wells in the world are less than 1000 m deep (IPCC, 2005), and why 1300-1500 m is considered as the depth limit of possible CO_2 storage in coals. Coal is a polymer-like substance that is often affected by the gas with which it is in contact.

Coal swells as CO_2 is adsorbed, which further reduces permeability and injectivity (IPCC, 2005). Coal swelling generally increases with increasing gas affinity to coal (e.g., CO_2 versus methane), and may reduce permeability by two orders of magnitude or more (Shi and Durucan, 2005). In addition, the injected CO_2 may react with the coal and/or formation water, leading to solids precipitation and further permeability reduction (Reeves and Schoeling, 2001; Zhang et al., 1993). Carbon dioxide is a "plasticizer" for coal, lowering the temperature required to cause the transition from a glassy, brittle structure to a rubbery, plastic structure (IPCC, 2005). Coal plasticization destroys the permeability that would allow CO_2 injection. Thus, these combined effects on permeability caused by the presence of CO_2 reduce the depth limit for CO_2 storage in coals to approximately 1,000 m.

The process of CO_2 trapping in coals at temperatures and pressures above the critical point is not well understood, and it seems that adsorption is replaced by absorption and the CO_2 diffuses into coal (Larsen, 2003). The transition from one process to the other is not sharp, but rather gradual. At the high temperature and pressure conditions that correspond to supercritical CO_2, it is not clear whether CO_2 is adsorbed by coal, occupies the pore space like a fluid with very low viscosity, or infuses into the coal matrix. Under these conditions coals are not a good storage medium because CO_2 might be highly mobile and migrate out of the coals into the adjacent strata or within the coals themselves, with the potential for leakage into shallow groundwater aquifers and even to the surface. Thus, until the basic science of CO_2 storage in coal advances to clarify these points, it seems that it would be safe to consider that CO_2 should be stored only in coal beds that are at such temperature and pressure conditions that CO_2 is in the gaseous phase. For hydrostatic conditions and average geothermal gradients this would correspond to depths in the 700-800 m range".

Therefore it is possible to consider a position in which:

- selective mining takes place in all major fields to depths of 600 m, and more in Jharia, Raniganj, Bokaro, Karanpura and Sohagpur
- CO_2 storage is not likely to take place <100 m below a mined seam, and
- CO_2 storage in coal seams should only take place where CO_2 is in the gaseous phase, i.e. above 700-800 m depth

If such a position indeed arises, there may prove to be very little scope for CO_2 storage in India's major coalfields. However, CO_2 storage may prove to be possible down to depths of 1000 m or more, so an indicative storage capacity calculation was made on the following basis, see also Table 2.14:

- All beds with coal of any grade to depth of 300m will not be available for storage of CO_2 as these are stipulated to be within the range of surface mining
- All coal beds with coking coal - prime, medium or semi coking - will not be available for CO_2 storage irrespective of depth
- All coal beds with superior grade non coking coal (Grade A to D) will not be available for storage of CO_2 irrespective of depth
- A parting of 100m undisturbed formation has to be maintained below the 300m depth floor
- On average, 30% of power grade non coking coal (Grade E-G) beds at depths between 400m (i.e. 300m less 100m barrier) and 600m will be available for CO_2 storage*
- On average, 10% of coal beds in coalfields where variable grades of coal occur at depths of 400m-600m depth will be available for CO_2 storage, in view of the selective mining of superior grade (A to D) coal beds
- On average 50% of inferior grade non coking coal under thick basalt / intertrappean cover and or geologically disturbed beds at depths of 400-600 m will be available for CO_2 storage
- 50% of coal within basins with coal beds of different grades at depths between 600-1200m will be available for CO_2 storage
- 100% of coal beds of inferior grade coal (E, F, G) at depths between 600 and 1200m will be available for CO_2 storage
- 100% of inferior grade non coking coal at depths of 600-1200 m under thick basalt / intertrappean cover and or geologically disturbed beds will be available for CO_2 storage
- Average CO_2 storage capacity of India's coal resources is 0.02 tonnes of CO_2 per tonne of coal

* with the exception of Godavari and Wardha Valley E Grade coal beds, which will be included in superior grade coal due to premium pricing.

Table 2.14 Summary of the assumptions made on CO_2 storage capacity of Indian coal

Depth of coal beds	Coal grade/category	CO_2 storage Capacity
0-300m	All grades of coal	Nil
300-600	Coking Coal	Nil
	Superior grade non coking coal	Nil
	Mixed (Superior: Inferior 1:1)	10%
	Inferior (E-G) grade	30%
	Inferior under thick trap	50%
600-1200	Coking coal	Nil
	Superior non coking coal	Nil
	Mixed grade (1;1 ratio)	50%
	Inferior grade under trap	100%

On the basis of these assumptions, the CO_2 storage capacity of the coalfields of India is estimated to be approximately 345 Mt CO_2. A more detailed breakdown is shown in Table 2.15.

Table 2.15 Breakdown of estimated CO2 storage capacity of Indian coalfields

State /Coalfield	Reserve at 300-600 m depth (Mt)	Reserve available for CO_2 storage 300-600m (Mt)	Est. CO_2 storage capacity 300-600 m (Mt)	Reserve at 600-1200 m depth (Mt)	Reserve available for CO_2 storage 600-1200m (Mt)	Est. CO_2 storage capacity 600-1200 m (Mt)	Estimated total CO_2 storage capacity (Mt)	Coal bed Quality
West Bengal								
Raniganj	7161	0	0	4018	0	0	0	Superior
Birbhum	3229	1615	32	981	981	20	52	Inferior
Bihar**								
Raniganj	519	0	0	see above	see above	see above	0	Superior
Jharia**	14122	0	0	5213	0	0	0	Coking
East Bokaro	1623	0	0	2349	0	0	0	Coking
Ramgarh	389	0	0	0	0	0	0	Coking
West Bokaro	445	0	0	0	0	0	0	Coking
North Karanpura	4221	0	0	0	0	0	0	Coking
South Karanpura	1840	0	0	840	0	0	0	Coking
Auranga	1290	387	8	71	71	1	9	Inferior
Hutar	12	4	0	0	0	0	0	Inferior
Rajmahal	3754	1126	23	0	0	0	23	Inferior
Madhya Pradesh								
Pench Kanhan	504	50	1	0	0	0	1	Mixed
Pathakhera	134	13	0	0	0	0	0	Mixed
Sohagpur	1316	0	0	104	0	0	0	Coking
Singrauli	4420	1316	26	44	44	1	27	Inferior

Chhattisgarh								
Sonhat	971	97	2	568	284	6	8	Mixed
Hansdeo	17	0	0	0	0	0	0	Mixed
Korba	2364	709	14	0	0	0	14	Inferior
Mand Raigarh	4619	1386	28	95	95	2	30	Inferior
Tatapani Ramkola	570	57	1	0	0	0	1	Mixed
Maharashtra								
Wardha	1539	154	3	13	6	0	9	Mixed
Kamptee	720	72	1	14	7	0	8	Mixed
Bander	22	2	0	0	0	0	0	Inferior
Orissa								
Ib River	8066	2430	48	0	0	0	48	Inferior
Talcher	8073	2422	48	1224	1224	24	72	Inferior
Andhra Pradesh								
Godavari	6514	651	13	3024	1512	30	43	Mixed
North East Region								
Makum	154	15	0	0	0	0	0	Superior
TOTAL	78608	12486	249	18558	4224	84	345	

** Jharia coalfield reserve is estimated within 0-600m depth cover.

Note that only eight of the coalfields have the capacity to store >10 Mt CO_2 and none have the capacity to store >100 Mt CO_2. Thus, in practice, it appears that storage in coal seams can make little contribution to reducing India's CO_2 emissions.

A more rigorous approach to calculating India's CO_2 storage capacity in coal seams could be undertaken but is beyond the scope of this study.

2.2.8 Estimated CO_2 storage capacity in deep saline aquifers in India

The CO_2 storage capacity in the deep saline water-bearing reservoir rocks (deep saline aquifers) of India is described qualitatively on a sedimentary basin-by-basin basis in Appendix 3. Areas not described in this analysis were not examined in detail because a first-pass assessment suggested that they may have little realistic CO_2 storage potential.

As expected in a country study (Bachu et al. 2007), insufficient geological information was available to determine the saline aquifer CO_2 storage capacity of any of the basins. However, a qualitative comparison of the saline aquifer storage capacity with that of the European sector is given in Appendix 4. This employs the same methodology as used in the IEAGHG European sector study (Wildenborg et al. 2006).

For assessment purposes, the basins were divided into categories of good, fair and limited saline aquifer CO_2 storage potential, as below. This process inevitably involved a degree of geological judgement and it is felt that the classification could be significantly refined with further work. Indeed, with further work, some basins are likely to be raised to categories of higher potential.

2.2.8.1 BASINS WITH GOOD POTENTIAL

Basins falling into this category contain hydrocarbon fields (proving containment of buoyant fluids over geological timescales) and there is expectation of good reservoir and seal quality at depths below 800 m over at least a significant part of the basin. They are:

- Assam Basin
- Assam-Arakan fold belt
- Mahanadi basin (deep water part)
- Krishna-Godavari Basin
- Cauvery Basin
- Mumbai Basin
- Cambay Basin
- Barmer Basin
- Jaisalmer Basin

The locations of these basins in relation to India's major sources of CO_2 are shown in Figure 2.6

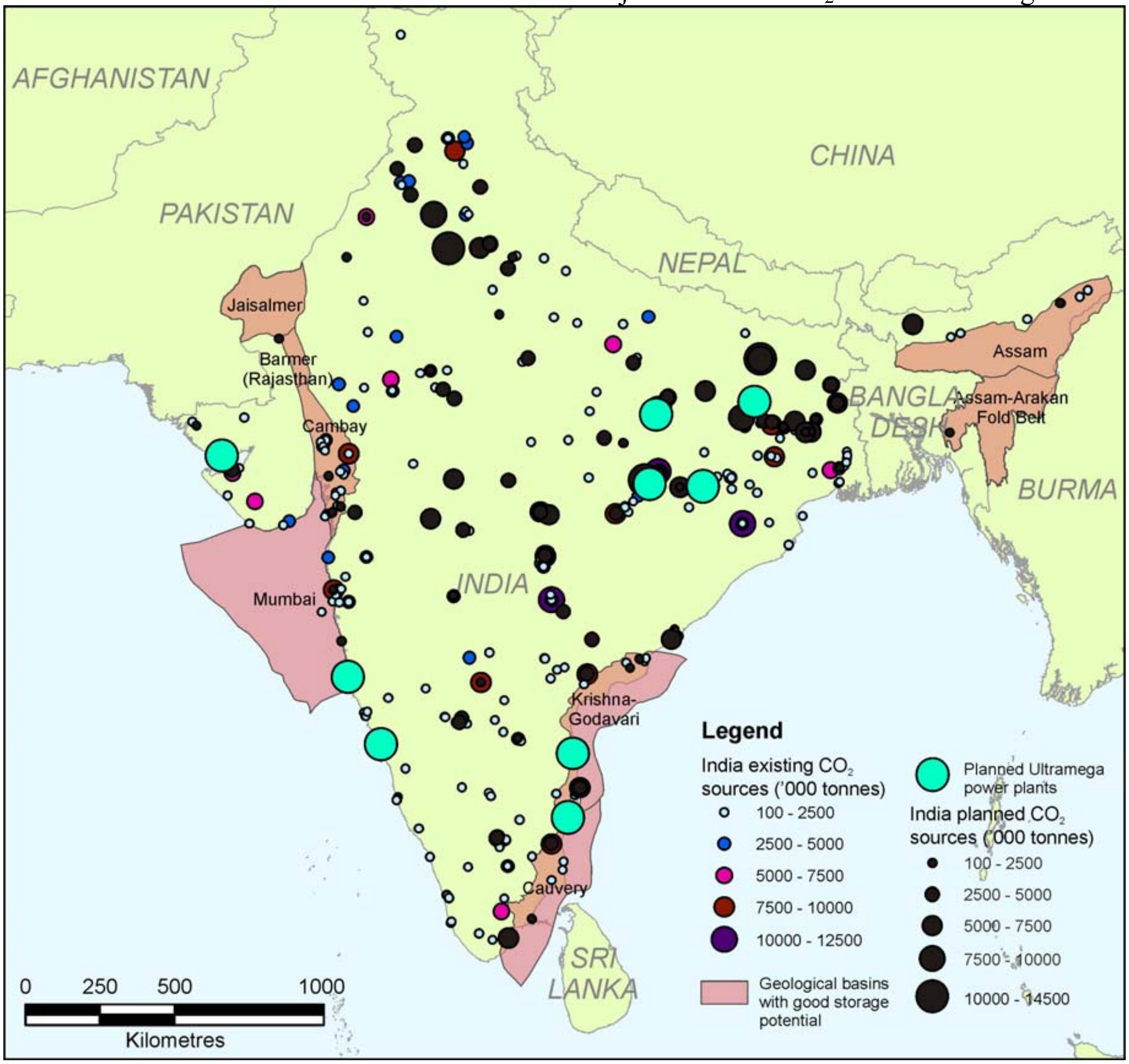


Figure 2.6 India's existing and planned CO_2 sources and geological basins with good storage potential

A summary of their perceived CO_2 storage potential is given below:

The Assam Basin

The presence of oil fields in the area south of the Brahmaputra River, at several stratigraphic levels in the Cenozoic section, indicates that this part of the Assam Basin has good potential to store buoyant fluids such as supercritical CO_2. Several apparently well-sealed reservoir horizons are present. The area north of the Brahmaputra lacks hydrocarbon fields, possibly because the seals are poorer but more likely due to lack of migration across the anticlinal Brahmaputra Arch that lies beneath the Brahmaputra. If the latter is the case, this area may also have potential.

The Assam Basin is remote from the main part of peninsula India and thus any CO_2 transport to Assam from peninsular India would have to be by pipeline, either around the 'chicken neck' to the north of Bangladesh, or across Bangladesh, or across Bangladeshi territorial waters.

The area is prone to some of the largest earthquakes ever recorded.

The Assam-Arakan Fold Belt

Gas fields are present in the outer parts of the fold belt itself, e.g. in the Surma Basin (NE Bangladesh), the Chittagong Hill Tracts (SE Bangladesh), Tripura and Mizoram. The presence of the Surma, Barail and Tipam groups in the Cachar-Tripura-Mizoram region, all of which contain sandstones, suggest that potential for CO_2 storage exists in these areas as well, at least west of the outcrops of Disang Shales. The main drawback is geographic: the Indian parts of the fold belt are remote from both major CO_2 sources and the main part of India. Overpressure may also be an issue.

The Mahanadi Basin

Good potential exists in deep water (i.e. water depths below 200 m), where there has been a major gas discovery, but this would likely be expensive to access. Both the onshore and shallow offshore basins should have some CO_2 storage potential, but the lack of hydrocarbon discoveries shoreward of the 200 m isobath (and thus a lack of proven containment of buoyant fluids) means that the potential in these areas is classified as only fair. Nevertheless, there is a potential regional seal in the Miocene-Pliocene section both onshore and offshore. In the offshore area, the most promising reservoirs may be the Palaeogene sandstones.

The Krishna-Godavari Basin

The Krishna-Godavari basin has excellent CO_2 storage potential both onshore and offshore, as the numerous hydrocarbon fields indicate the presence of traps that can retain buoyant fluids at several stratigraphic levels. Good porosity and permeability are present in some of these fields, e.g. the Ravva field, which is offshore. Further potential undoubtedly exists in deep water further offshore.

The Cauvery Basin

The presence of oil and gas fields in the Cauvery Basin indicates that the potential to store CO_2 in this area is high. This is particularly so in Mid- to Upper Cretaceous sequences where reservoir quality is good and there are interbedded seals.

The Mumbai Basin

The Mumbai Basin is a huge offshore area which appears to have good potential for CO_2 storage. The majority of reservoirs in this region are carbonates, so CO_2/water/rock reactions need to be considered. Moreover, reservoir properties can be quite variable. Post-Miocene shales form a regional cap rock over the whole Mumbai Offshore, except for the Ratnagiri Block. Overpressured formations may have to be avoided.

The Cambay Basin

There is good CO_2 storage potential in the Cambay Basin, demonstrated by the presence of numerous oil and gas fields. The Tarapur Shale is a regional cap rock that lies above the main reservoir rocks, which are of Middle-Upper Eocene age. Offshore, in parts of the Gulf of Cambay, hydrocarbons have been trapped in domal structures capped by the overlying Miocene Kand Shale. There is good potential for EOR in the oil fields of the Cambay Basin.

The Barmer Basin

The Barmer Basin is the northwards continuation of the Cambay Basin into the state of Rajasthan. There is likely to be excellent future potential for CO_2 storage in the Barmer Basin, both for EOR in the oil fields once these are developed, and in the aquifers. Projected secondary recovery by waterflooding in the main fields is predicted to be only in the order of 10-30% of oil in place.

The Jaisalmer Basin

The Jaisalmer Basin has potential for CO_2 storage, particularly in the western Kishangarh and Shahrgarh sub-basins where gas fields prove the potential to contain buoyant fluids.

2.2.8.2 Basins with fair potential

These contain one or more potential regional seals, underlying reservoirs at depths >800 m and potential structural closures. However, in these basins, containment of buoyant fluids over geological timescales is not yet proven by the discovery of hydrocarbon fields. These basins are:

- Mahanadi Basin (onshore and nearshore part)
- Bikaner-Nagaur Basin
- Kutch Basin

The location of these basins, the basins with good potential and the major sources of CO_2 are shown in Figure 2.7 Summaries of the potential of these basins follow:

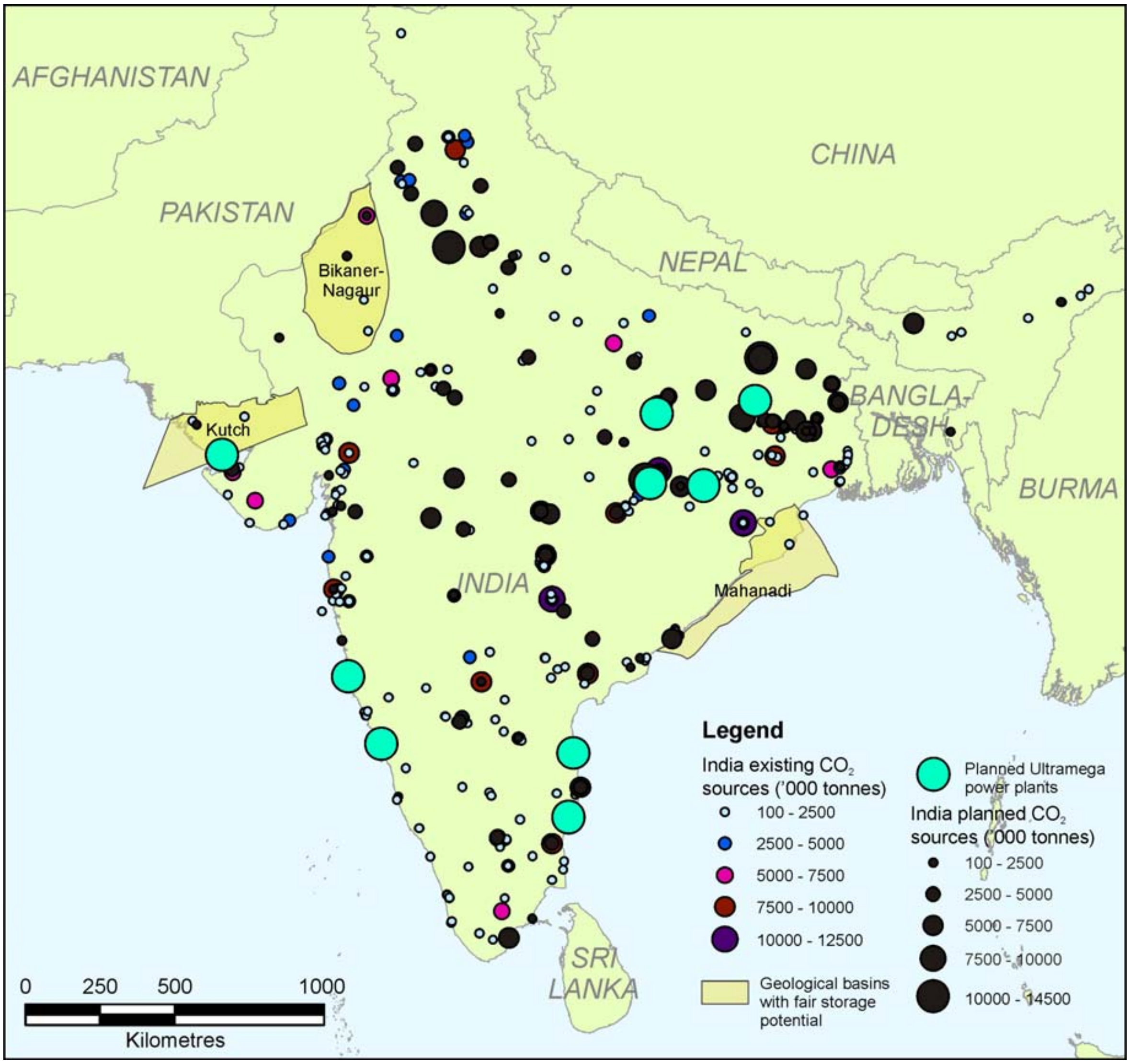


Figure 2.7 India's existing and planned CO_2 sources and geological basins with fair storage potential

The Mahanadi Basin (onshore and shallow water offshore)

Both the onshore and shallow offshore basins should have some CO_2 storage potential, but the lack of hydrocarbon discoveries shoreward of the 200 m isobath (and thus a lack of proven containment of buoyant fluids) means that the potential in these areas is classified as only fair. Nevertheless, there is a potential regional seal in the Miocene-Pliocene section both onshore and offshore. In the offshore area, the most promising reservoirs may be the Palaeogene sandstones.

The Bikaner-Nagaur Basin

Some CO_2 storage potential may exist in the Proterozoic reservoirs beneath the Hanseren Evaporite Formation, i.e. the Jodhpur Sandstone and the Bilara Dolostone. However, this cannot be quantified at present.

The Kutch Basin

In the Kutch Mainland, the Upper-Jurassic top Jhuran sandstones are potential reservoir rocks which are buried to depths of around 800-1295 m therefore potentially suitable for CO_2 storage. In the Pacham Island area, Mesozoic cover is possibly too thin to be of interest for CO_2 storage. In eastern Kutch, sands of the Lower Khadir Formation are at sufficient depth to be considered for CO_2 storage and capped by shales. Further study is required to firm up the storage potential in this basin.

2.2.8.3 Basins with limited potential

Porous and permeable reservoir are absent or not sealed in these basins, or the basins lack structural closures, or are in structurally complex fold belts, or they face major potential conflicts of use. Basins in this category are:

- Ganga Basin (and Punjab Shelf)
- Bengal Basin (Indian part)
- Vindhyan Basin
- Cuddapah Basin
- Chhatisgarh Basin
- Konkan-Kerala Basin
- Narmada Basin
- Saurashtra Basin
- Rajmahal Basin
- Pranhita-Godavari Basin
- South Rewa Basin
- Satpura Basin
- Damodar Valley Basins

These are shown in Figure 2.8. The reasons that these basins are considered to have limited potential at present are given below. It is probably premature to write any of them off completely however, given the current state of knowledge about CO_2 storage and the fact that many of them are relatively poorly explored due to a perceived lack of hydrocarbons.

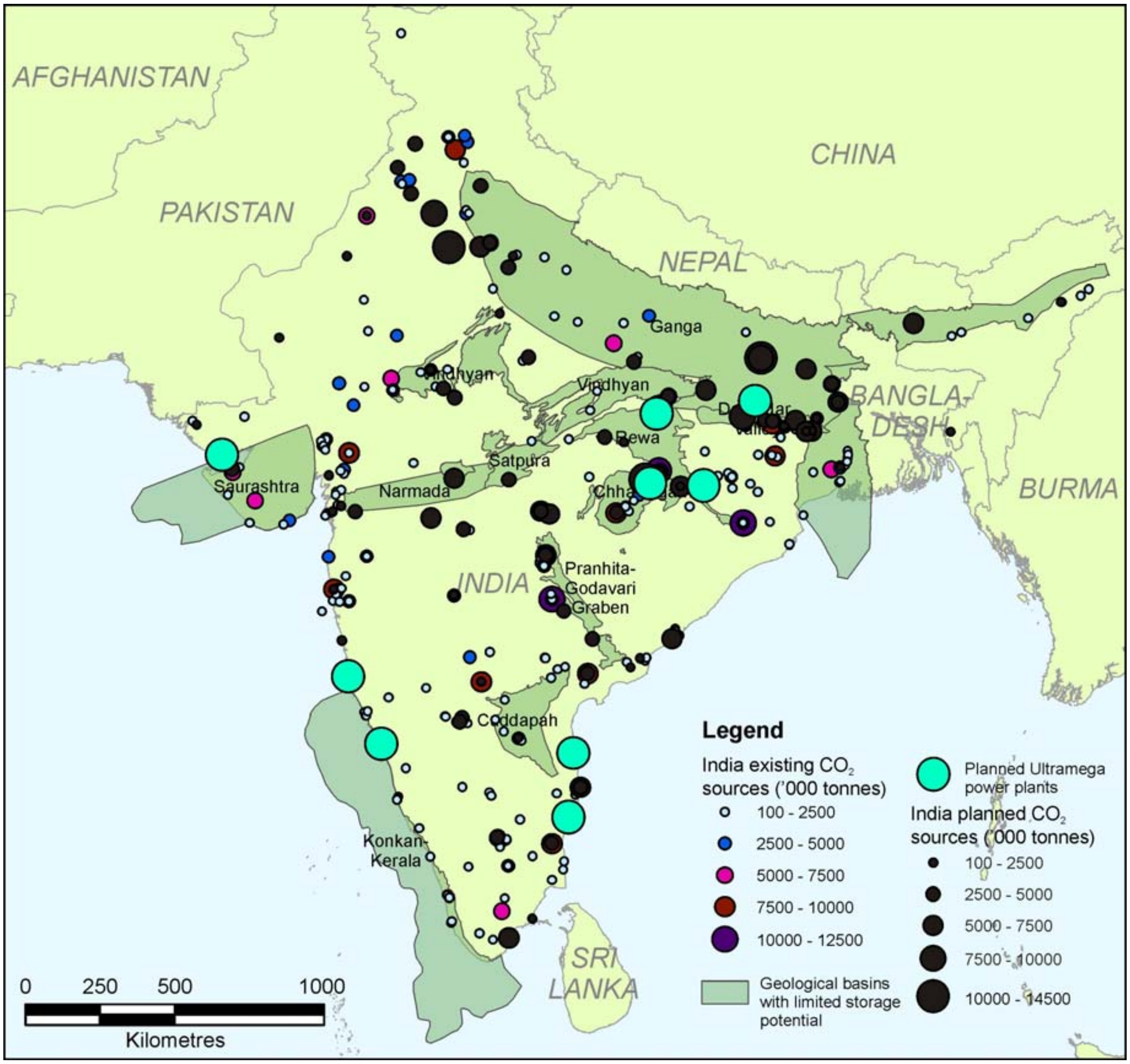


Figure 2.8 India's existing and planned CO_2 sources and geological basins with limited storage potential

The Ganga Basin and Punjab Shelf

The Ganga Basin, which lies beneath the densely populated agricultural region of the Ganges Plain, is considered to have limited potential because there is a potential conflict of interest between groundwater supply and CO_2 storage. This may be controversial because geologically the Ganga Basin contains 4-6 km of Cenozoic and Quaternary alluvium that thins southwards and eastwards onto older sedimentary rocks. Were it not for the potential conflict of interest, this basin could have significant CO_2 storage potential. Fewer wells have been drilled in the Ganga basin and Punjab Shelf than in prospective areas elsewhere in India and hence some areas and sequences are still poorly known. By 1991, only 15 deep exploration wells had been drilled.

The Bengal Basin

The western (Indian) part of the Bengal Basin may have some CO_2 storage potential, but the lack of proven seal and closure means that prospects are classified as limited at present. There is excellent potential in the eastern part of the basin, in eastern Bangladesh, where there are gas fields in the basin both onshore and offshore.

The Vindhyan, Chhatisgarh and Cuddapah Basins

The Vindhyan, Chhatisgarh and Cuddapah Basins are Proterozoic basins – the sedimentary rocks within them are generally about 1500-500 million years old. Such information as is available at present suggests that these rocks are highly indurated and have insufficient permeability for large-scale CO_2 storage.

The Konkan-Kerala Basin

The Konkan-Kerala Basin is perceived to have poor reservoir potential and may lack structural closures.

The Narmada and Saurashtra Basins

The Narmada and Saurashtra basins may have potential beneath the Deccan Trap, but this is unproven and this part of the succession is likely to be difficult to image seismically.

The Prahnita-Godavari, Satpura, Rajmhal, Damodar Valley and South Rewa Basins

The Prahnita-Godavari, Satpura, Rajmahal, Damodar Valley and South Rewa Basins are Gondwana Basins some of which are relatively restricted in size and depth. Nonetheless, some are large, contain significant thicknesses of sandstone and may have storage potential at depth (Mondal 2006). For example sandstones in the Rajmahal coalfields, which continue at depth beneath the Rajmahal Traps, and sandstones within the Lower Gondwana succession in the Pench-Kanhan-Tawa valley area may have potential at depth in the centre of the Satpura Basin. It is definitely too early to write off the CO_2 storage potential of some of these basins, but further investigation is required to prove up potential.

Some of the Gondwana Basins are actively being mined for coal. These coal-bearing areas may have potential to store limited amounts of CO_2 adsorbed onto coal (see section 2.2.2 above).

2.3 MATCHING CO_2 SOURCES AND POTENTIAL CO_2 STORAGE SITES IN INDIA

Figure 2.6 shows the geographical relationship between the major sources of CO_2 in India and the sedimentary basins with good, fair and limited storage potential. N.B. The basins rated as good are the hydrocarbon-bearing basins, so they also contain all the potential in oil and gas fields.

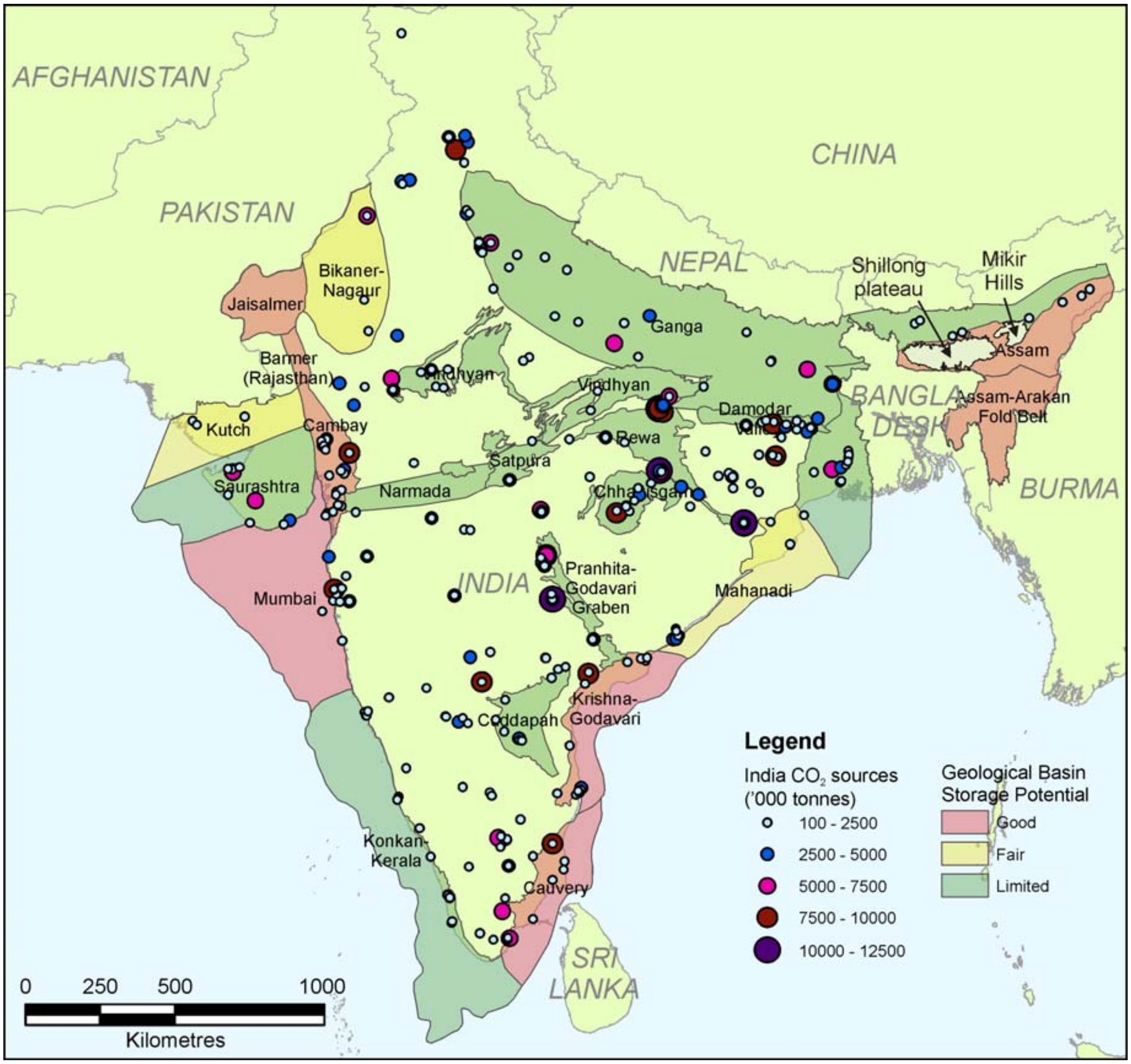


Figure 2.9 Geographical relationship between existing CO_2 sources and sedimentary basins in India

It may be seen that sources in the NW of peninsula India and along the SE coast have good nearby storage potential, whereas those in SE, Central and northern India do not. However, there is a large area of fair potential in the Mahanadi Basin, where there is a fair chance that emissions from the major clusters of sources in the NE peninsula India could be stored. The good potential in Assam and the Assam-Arakan Fold Belt appears to be stranded.

Figure 2.7 shows the relationship between the planned new CO_2 sources and the sedimentary basins with good or fair storage potential. The nine planned ultra mega power plants are identified separately.

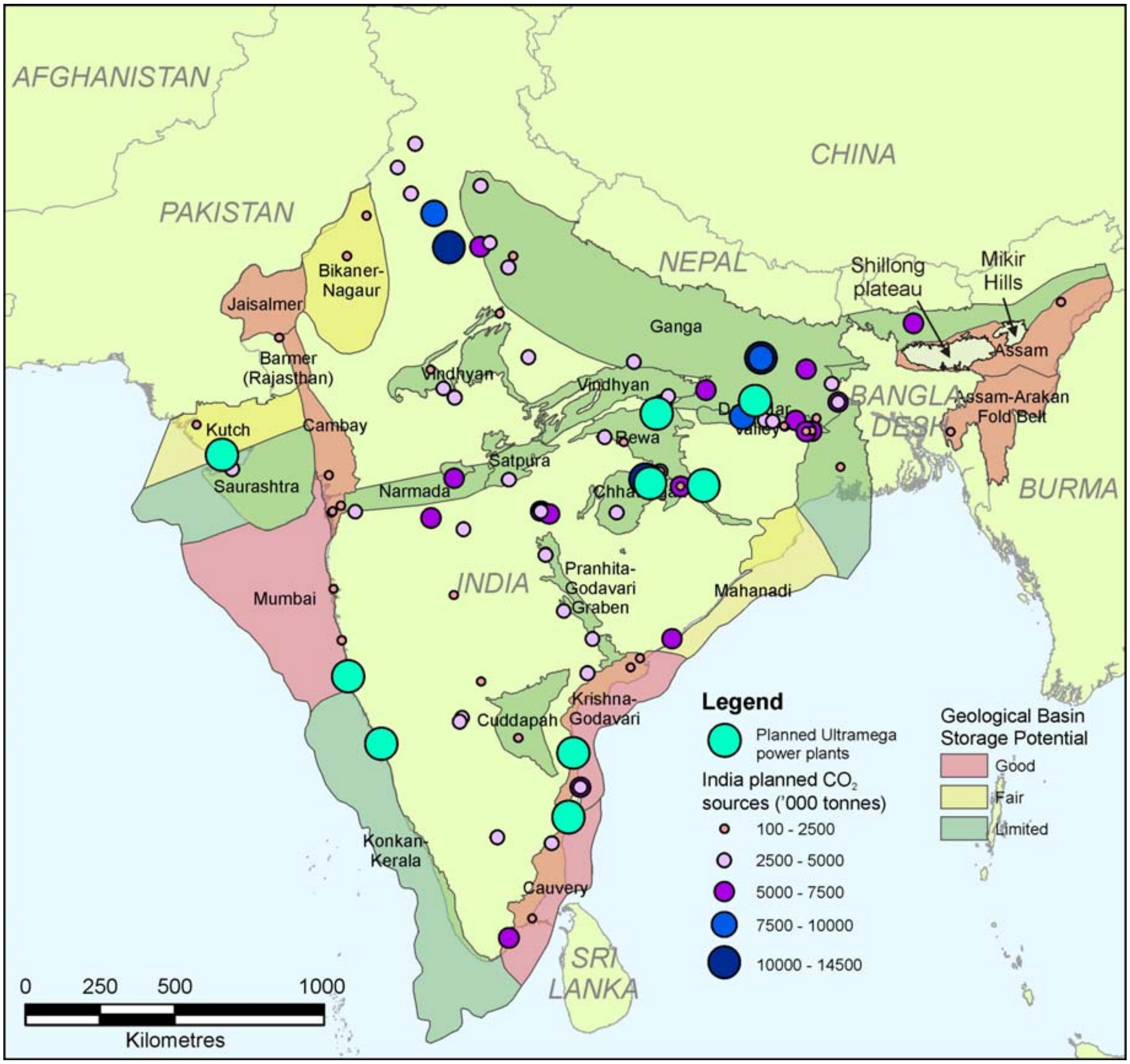


Figure 2.10 Geographical relationship between planned CO_2 sources and sedimentary basins in India

The geographical relationships are essentially similar. Again it may be seen that many of the planned sources are distant from sedimentary basins with good storage potential, and the good potential in Assam and the Assam-Arakan fold belt appears stranded. Nevertheless there are several major sources on the SE coast and the area NE of Mumbai that appear well placed to take advantage of CCS technology.

2.4 PRELIMINARY COST ESTIMATES FOR CCS IN INDIA

2.4.1 Introduction

This part of the study develops cost flow sheets for key CO_2 capture and storage (CCS) components for global and Indian conditions and estimates future cost developments for CCS technology. It also assesses the availability of key cost data for the development of more robust cost estimates in the future.

With almost all other sub-systems in the CCS chain being a mature market currently, capture sub-systems account for 60-80% of the CCS system costs for geological storage (Table 2.16). Their high costs are the major hurdle in CCS acceptability on commercial scales as a competitive CO_2 sequestration option with respect to other near-zero CO_2 emission technologies. Costs vary considerably in both absolute and relative terms across countries and type of capture systems. The costs of CCS in tandem with an IGCC or a combined cycle gas plant have higher uncertainty since they are not yet built on a full commercial scale. In the future, the costs of CCS are projected to be reduced by research and technological development, learning curves, and economies of scale.

Table 2.16 The current global cost ranges for CCS system components

CCS system components	*Cost range*	*Remarks*
Capture from a coal- or gas-fired power plant	15 - 60 US$/t$CO_2$ net captured	Net costs of captured CO_2, compared to the same plant without capture
Capture from hydrogen and ammonia production or gas processing	5 - 50 US$/t$CO_2$ net captured	Applies to high-purity sources requiring simple drying and compression
Capture from other industrial sources	25 - 115 US$/t$CO_2$ net captured	Range reflects use of a number of different technologies and fuels
Transportation	1 - 8 US$/t$CO_2$ transported	Per 250 km pipeline or shipping for mass flow rates of 5 (high end) to 40 (low end) MtCO_2/yr.
Geological storage	0.5 - 8 US$/t$CO_2$ injected	Excluding potential revenues from EOR or ECBM.
Geological storage: monitoring and verification	0.1 - 0.3 US$/t$CO_2$ injected	This covers pre-injection, injection, and post-injection monitoring, and depends on the regulatory requirements
Ocean storage	5 - 30 US$/t$CO_2$ injected	Including offshore transportation of 100 - 500 km, excluding monitoring and verification
Mineral carbonation	50 - 100 US$/t$CO_2$ net mineralized	Range for the best case studied. Includes additional energy use for carbonation

Source: Updated version of a similar table from IPCC, 2005

2.4.2 Cost components and plants - fuels covered

For the purpose of this report, we have analyzed the costs components of the three main modules of the CCS system, namely capture, transport and storage. The cost components are analyzed for both global and Indian conditions to enable cost comparisons and furthermore, to use the global cost data as basis for some of the Indian costs estimates.

The capture cost analysis includes the cost of capture from pulverized coal (PC), ultra super critical (USC), integrated gasification combined cycle (IGCC) coal power plants and also natural gas processing plants. The components analyzed are capture & compression capital costs, flue gas cleaning capital costs, capture & compression operation and maintenance (O&M) costs and flue gas cleaning O&M costs. Since technical data for Indian conditions are still limited, it was decided not to go into further detail with further disaggregated sub-components of capture costs at this point. The transport cost analysis includes the capital and O&M costs of on-shore and off-shore pipelines with a range of different diameters. The storage cost analysis includes Enhanced Oil Recovery (EOR), Enhanced Coal Bed Methane (ECBM), depleted oil & gas reservoir and saline aquifer storage. All storage cost estimates are based on on-shore storage.

For all O&M costs the Net Present Value (NPV) is calculated. The NPV calculations use a discount rate of 8 per cent and a plant lifetime of 30 years. The total NPV of the different cost components are found by summing the overnight capital cost and the O&M NPV costs.

Future cost developments for the three main CCS modules are estimated up to 2030. The estimates are based on cost projections by the IEA and REN21 for other relevant and alternative energy technologies.

For cost data given in Indian Rupees a conversion factor of about 44 Rs/USD is used. For cost data given in Danish Crowns a conversion factor of about 5.6 Danish Crowns/USD is used. The cost data given in USD are from the late 1990s to early 2000s. Due to uncertainty in the cost data, no adjustments have been made to correct for exchange rate variations and inflation.

The numbers given in the tables have been rounded, taking into account the data uncertainties.

2.4.3 Flow sheets for estimates of global cost

The global cost estimates are based on data obtained mainly from American and European sources and reflect the going global market price for the different CCS components. Since more data on CCS systems exists on a global level, it is possible to use the global costs estimates to validate, and in some cases as basis for, the Indian cost analysis.

2.4.3.1 CAPTURE COSTS

The results from the capture cost analysis are shown in Table 2.17. The capture costs for PC, USC, IGCC and gas processing plants are broken down into capture & compression capital costs, flue gas cleaning capital costs, capture & compression O&M costs and flue gas cleaning O&M costs. In addition the NPV of the O&M costs are calculated.

The capture & compression capital cost for a PC plant is based on a capture system applied to a new-build, sub-critical bituminous coal-fired plant, with an efficiency of 39 per cent. The capture system is assumed to have a 95 percent capture efficiency using a MEA sorbent (IPCC, 2005). The annual O&M costs of the capture & compression system are assumed to be 4 per cent of the capital cost (Azar et al, 2006). The energy penalty of the capture & compression system is not included in the O&M costs, but is estimated to be a 40 per cent increase in input per KWh (IPCC, 2005). The capital cost of flue gas cleaning is based on data from The World Bank (2007). Since ESP systems are standard equipment in most new-build and existing power plants, their costs are assumed to be included in the plant capital cost. Therefore only the cost of flue gas desulphurization (FGD), low NO_x burner and selective catalytic reduction (SCR) are included in the flue gas cleaning system required for a CCS system. Some of the cost numbers are from the mid/late 1990s and could therefore be expected to be slightly overestimated as the costs may have declined. However, The World Bank's estimates vary by more than 100% and hence a mean cost is thought to be a good estimate of the costs in the beginning of the 21st century. The flue gas cleaning O&M costs are also based on data from The World Bank (2007). Since The World Bank gives the O&M costs in \$/MWh, the costs have been converted to \$/KW/yr by applying them to a hypothetical power plant with a capacity factor of 0.75.

The capture & compression capital cost for the USC plant is based on a capture system applied to a new-build, bituminous coal fired plant, with an efficiency of 41 per cent. The capture system is assumed to have a 90 percent capture efficiency using a MEA sorbent (IPCC, 2005). The annual capture & compression O&M cost is assumed to be 4 per cent of the capital cost similar to the PC plant (Azar, C. et al, 2006). The capture energy penalty is estimated to be a 31 per cent increase in input per KWh (IPCC, 2005). The cost of flue gas cleaning is assumed to be the same as for the PC plant.

The capture & compression capital cost for the IGCC plant is taken as an average of capture systems applied to new-build, bituminous coal fired IPCC plants, with efficiencies of 38-47 per cent. The capture technology used in all cases is Selexol (IPCC, 2005). The annual capture & compression O&M cost is assumed to be 4 per cent of the capital cost as for the plants above (Azar, C. et al, 2006). The capture energy penalty is estimated to be a 19 percent increase in input per KWh (IPCC, 2005). Since no significant flue gas cleaning is necessary for this plant type, this parameter has not been included.

The gas processing plant costs included in the global estimate are based on data from the In Salah project (Haddadji, R., 2006). Since the cost cannot be given in $/KW it is given for an injection capacity of 1, 0 Mt CO_2/yr. The annual O&M cost is again assumed to be 4 per cent of the capital cost. No flue gas cleaning costs are included.

Table 2.17 Global capture system costs

Base plant	Capital costs, Capture & compression	Capital costs, Flue gas cleaning	Capital costs, TOTAL	O&M costs, Capture & compression	O&M costs, Flue gas cleaning	O&M costs TOTAL	NPV O&M Costs	NPV TOTAL
PC	*1 100 $/KW*	*210 $/KW*	*1 310 $/KW*	*40 $/KW/yr*	*110 $/KW/yr*	*150 $/KW/yr*	*1 700 $/KW*	*3 000 $/KW*
USC	*730 $/KW*	*210 $/KW*	*940 $/KW*	*30 $/KW/yr*	*110 $/KW/yr*	*140 $/KW/yr*	*1 530 $/KW*	*2 470 $/KW*
IGCC	*500 $/KW*	-	*500 $/KW*	*20 $/KW/yr*	-	*20 $/KW/yr*	*230 $/KW*	*730 $/KW*
Gas Processing plant, Capacity 1,0 Mt CO_2/yr	*$ 100 mill*	-	*$100 mill*	*4,0 mill $/yr*	-	*4,0 mill $/yr*	*$ 45 mill*	*$ 145 mill*

2.4.3.2 TRANSPORT COSTS

The global transport costs are shown in Table 2.18. Since very little publicly available data exists on CO_2 pipelines, the cost of natural gas pipelines can be used as a good estimate of CO_2 pipeline costs (Heddle et al. 2003). However, cost of CO_2 pipelines can be slightly higher than natural gas pipelines due to increased pipeline corrosion and, for on-shore pipelines, a need for thicker walls to handle pressures of 100-150 bar (Heddle et al. 2003). The on-shore costs are based on data from USA (Heddle et al. 2003), while the off-shore costs a based on European data (Hansen, T. H., personal communication). The off-shore pipeline costs are based on a 50 km pipeline and hence a shorter pipeline might have higher capital costs per km.

Table 2.18 Global transport costs

Pipeline type	Capital costs ($/Km)	O&M costs ($/Km/yr)	NPV O&M costs ($/Km)	NPV TOTAL ($/Km)
On-shore 8 Inches	*180 000*	*3 100*	*35 000*	*220 000*
On-shore 16 Inches	*280 000*	*3 100*	*35 000*	*320 000*
On-shore 24 Inches	*520 000*	*3 100*	*35 000*	*560 000*
Off-shore 8 Inches	*1 070 000*	*20 000*	*230 000*	*1 300 000*
Off-shore 16 Inches	*1 410 000*	*20 000*	*230 000*	*1 640 000*
Off-shore 24 Inches	*1 870 000*	*20 000*	*230 000*	*2 100 000*

2.4.3.3 STORAGE COSTS

The global storage costs are shown in Table 2.19. For the sake of consistency all costs are given on a modular basis, since EOR and ECBM systems consist of modules of injection and production wells. All storage modules consist of 10 injection wells apart from the saline aquifer module, which only consists of one large well. It is important to note the large differences in CO_2 injection capacity for the different modules. The injection rates and module costs are based on a report on CO_2 storage by Heddle et al.

(2003) and reflect American conditions. The costs of EOR and ECBM are given directly in the report while the costs for depleted oil and gas reservoirs are adjusted to a 10 well modular system using formulas given in the report. For the saline aquifer option the base case given in report is used (Heddle et al. 2003). For EOR, the CO_2 injection effectiveness is estimated to be 170 scm CO_2 per bbl enhanced oil while it for ECBM is estimated to be 2 scm CO_2 per scm enhanced methane. In the EOR case CO_2 recycling is needed since some CO_2 is produced along with the enhanced oil. The storage costs are based on well depths of about 1200 m for EOR, 600 m for ECBM, 1500 m for depleted oil & gas reservoirs and 1200 for a saline aquifer (Heddle et al, 2003). In the storage cost estimates it is assumed that the CO_2 has a pressure of at least 103 bar when it reaches the storage destination. For the EOR and ECBM processes, additional energy requirements are included in the O&M costs (Heddle et al. 2003).

Table 2.19 Global storage costs

Storage type	Injection wells per module	CO_2 Injection per module (ton/day)	Injection & storage capital costs ($/module)	Injection & storage O&M costs ($/module/yr)	NPV O&M costs ($/module)	NPV TOTAL ($/module)
Enhanced Oil Recovery (EOR)	10	130	3260 000	480 000	5430 000	8690 000
Enhanced Coal Bed Methane (ECBM)	10	530	6570 000	465 000	5240 000	11810 000
Depleted Oil Reservoir	10	1540	5470 000	530 000	5970 000	11440 000
Depleted Gas Reservoir	10	3520	5400 000	530 000	5960 000	11360 000
Saline Aquifer	1	7390	2150 000	100 000	1130 000	3280 000

2.4.4 Flow sheets for estimation of Indian costs

The Indian cost estimates are based on technical data from India combined with data on global CCS costs. Currently, only limited data exists for Indian conditions and hence it has in some cases been necessary to make a more general cost estimate.

2.4.4.1 INDIAN CAPTURE COSTS

The estimates of Indian capture costs are shown in Table 2.20. As in the global cost analysis, the capture costs for PC, USC, IGCC and gas processing plants are estimated. Since no capture system has been applied to an Indian power plant to date, costs estimates are derived from the capital costs of new Indian power plants given by the Indian National Thermal Power Corporation (NTPC) combined with global capture cost estimates from IPCC.

For capture systems applied to an Indian PC plant, a plant capital cost of $900/KW is used as basis (Sonde 2006, 2007). The capture system cost is then found assuming that the capture system applied to a PC plant has a capital cost of 87 percent of the power plant cost (IPCC 2005). The annual capture system O&M cost is estimated to be 4 percent of the capital cost as in the global case. The energy penalty of the capture system is as for the global case estimated to be a 40 percent increase in input per KWh (IPCC 2005). The flue gas cleaning costs are like the global estimates based on data from The World Bank.

For capture systems applied to an Indian USC power plant, a plant capital cost of $1140/KW is used (Sonde 2006). The capture system cost is then found assuming that the capture system applied to an USC plant has a capital cost of 61 percent of the power plant cost (IPCC 2005). The annual capture system O&M cost is again estimated to be 4 percent of the capital costs. The capture energy requirement is like in the global case estimated to be a 31 percent increase in input per KWh (IPCC, 2005). The flue gas cleaning costs are also equivalent to the global estimate.

For capture systems applied to an Indian IGCC plant, a plant capital cost of $1400/KW is used (Sonde 2006). The capture system cost is then estimated assuming that the capture system applied to an IGCC plant has a capital cost of 37 percent of the power plant cost (IPCC 2005). The annual capture system O&M cost is again estimated to be 4 percent of the capital costs. The capture energy requirement is as for the global case estimated to be a 19 percent increase in input per KWh (IPCC 2005). No flue gas cleaning costs are included.

The capture costs of an Indian gas processing plant are based on a planned EOR facility at the Hazira Plant operated by the Oil and Natural Gas Corporation (ONGC). The plant has a capture capacity of about 0.4 Mt CO_2/yr and is expected to operate for 30-35 years (Kumar et al. 2007). The capital cost consists of capture costs, compression & dehydration costs and chemicals costs and is estimated to about $62.5 million for the whole plant. The annual O&M costs are as for the earlier estimates assumed to be 4 percent of the capital costs. No flue gas cleaning equipment is included.

Table 2.20 Indian capture system costs

Base plant	Capital costs, Capture & compression	Capital costs, Flue gas cleaning	Capital costs, TOTAL	O&M costs, Capture & compression	O&M costs, Flue gas cleaning	O&M costs TOTAL	NPV O&M Costs	NPV TOTAL
PC	*890 $/KW*	*210 $/KW*	*1 100 $/KW*	*35 $/KW/yr*	*110 $/KW/yr*	*145 $/KW/yr*	*1 600 $/KW*	*2 700 $/KW*
USC	*820 $/KW*	*210 $/KW*	*1 030 $/KW*	*30 $/KW/yr*	*110 $/KW/yr*	*140 $/KW/yr*	*1 560 $/KW*	*2 600 $/KW*
IGCC	*520 $/KW*	-	*520 $/KW*	*20 $/KW/yr*	-	*20 $/KW/yr*	*240 $/KW*	*760 $/KW*
Gas Processing plant, capacity 0,4 Mt CO_2/yr	*$ 62,5 mill*	-	*$ 62,5 mill*	*2,5 mill $/yr*	-	*2,5 mill $/yr*	*$ 28 mill*	*$ 90 mill*

2.4.4.2 INDIAN TRANSPORT COSTS

The Indian transport costs are shown in Table 2.21. The on-shore pipeline cost estimates are based on the cost of the CO_2 pipeline at the Hazira Plant (16 inches) and natural gas pipelines from the Indian Infraline Database (30, 42 & 48 inches), (Kumar et al. 2007; Infraline Database 2007; Dhar 2006). The annual on-shore O&M costs are estimated based on the global numbers. The off-shore capital costs are found using a global pipeline model for a 50 Km off-shore pipeline under Indian conditions (Hansen 2007). The off-shore O&M costs are assumed to be 90 per cent of the global costs, since global and Indian costs are expected to be almost equal.

Table 2.21 Indian transport costs

Pipeline type	Capital costs ($/Km)	O&M costs ($/Km/yr)	NPV O&M costs ($/Km)	NPV TOTAL ($/Km)
On-shore 16 Inches	*230 000*	*2 500*	*30 000*	*260 000*
On-shore 30 Inches	*820 000*	*3 500*	*40 000*	*860 000*
On-shore 42 Inches	*1 090 000*	*5 000*	*60 000*	*1 150 000*
On-shore 48 Inches	*1 140 000*	*5 000*	*60 000*	*1 200 000*
Off-shore 8 Inches	*940 000*	*18 000*	*200 000*	*1 150 000*
Off-shore 16 Inches	*1 230 000*	*18 000*	*200 000*	*1 430 000*
Off-shore 24 Inches	*1 550 000*	*18 000*	*200 000*	*1 750 000*

2.4.4.3 INDIAN STORAGE COSTS

The Indian storage costs are shown in Table 2.22. As for the global estimates, the costs are given on a modular basis. The EOR costs are based on data from the EOR system at the Hazira Plant, with an estimated CO_2 injection capacity of about 98 tonne/day/well for a 12 well module (Kumar et al. 2007). The O&M costs for the EOR system is assumed to be about

$25000/well/year and this level is used for all Indian storage options. The EOR facility is planned to be in operation for about 30 years and during this period it is expected that 5 Mt oil will be recovered (Kumar et al., 2007). The cost of ECBM is not included in this study due to high uncertainty in its costs and application data in India (Singh 2007).

The Indian costs of depleted oil/gas reservoir and saline aquifer storage are based on global costs, since no reliable cost data are available. The Indian cost of depleted oil/gas reservoir storage is estimated to about 80 per cent of the global cost while the cost of saline aquifer storage is estimated to about 90 per cent of global cost.

Table 2.22 Indian storage costs

Storage type	Injection wells per module	CO_2 injection per module (ton/day)	Injection & storage capital costs ($/module)	Injection & storage O&M costs ($/module/yr)	NPV O&M costs ($/module)	NPV TOTAL ($/module)
Enhanced Oil Recovery (EOR)	12	1 180	34 090 000	300 000	3 380 000	37 470 000
Depleted Oil/Gas Reservoir	10	2 500	4 350 000	300 000	3 380 000	7 730 000
Saline Aquifer	1	7 400	1 940 000	75 000	850 000	2 790 000

2.4.4.4 Future cost curve estimates

The future cost development of CCS technologies is estimated in this section. The cost estimates are based on cost projections of other alternative energy technologies (Christensen et al. 2006 & IEA 2005). As shown in Figure 2.8 and 2.9, the future cost projections of alternative technologies vary significantly, and the expected cost reductions are strongly dependent on the maturity of the technology. While the costs of solar thermal and biomass technology are expected to decrease by 20 percent until 2030, the cost of solar PV is expected to decrease by 60 percent and fuel cell vehicles by as much as 80 per cent.

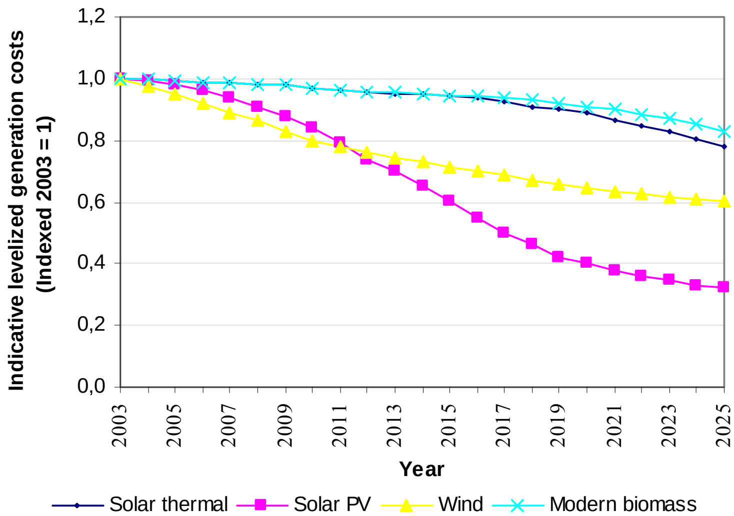


Figure 2.11 Future cost development of renewable energy technologies

Sources: Christensen et al., 2006 as derived and compiled from EWEA, 2003; Renewable Hydrogen Forum, 2003 (http://www.ases.org/hydrogen_forum03/Forum_report_c_9_24_03.pdf); http://europa.eu.int/comm/energy_transport/atlas/htmlu/rover31.html; and http://www.ucsusa.org/clean_energy/renewable_energy/page.cfm?pageID=100;

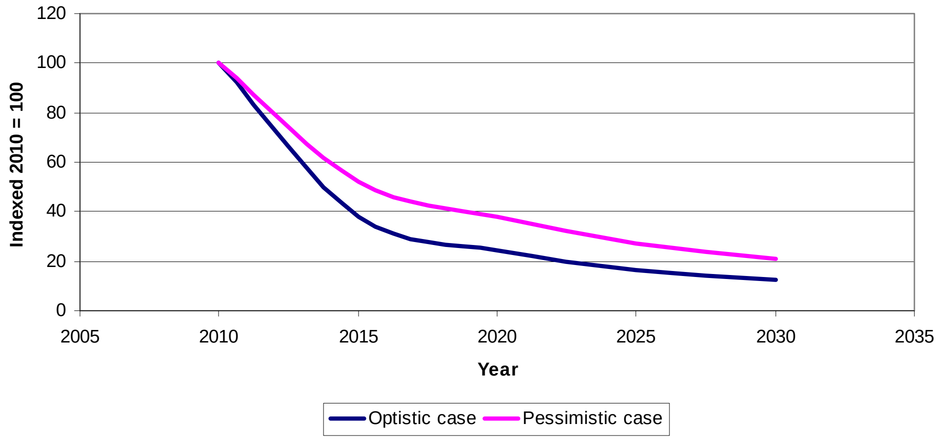


Figure 2.12 Future cost development of fuel cell vehicles, source IEA 2005

Because the three main modules of the CCS system are at different technology maturity levels, their cost projections vary greatly. The capture system is still at an early research, development and demonstration phase and hence major cost reductions are expected to be achievable in the future. The transport costs are not expected to decrease considerably since pipeline transport is used all over the world and is a mature technology. Even though geological storage of CO_2 is only taking place at a very limited scale at this point, many of the technologies are similar to those currently used in the oil and gas industry. Therefore the storage cost decrease is not expected to be as high as for the capture technology. However since capture costs constitute the major cost components in the CCS chain, their cost reduction will greatly influence the overall cost curve of CCS technology. Figure 2.10 shows the expected future cost development for the capture, transport and storage systems.

As can be seen in Figure 2.9 large cost reductions can be expected for immature technologies such as fuel cell vehicles. Since capture technologies are still relatively immature, large cost reductions might be achieved in the future. Therefore the projection shown in Figure 2.10 is relatively conservative. The speed of their maturity would also depend upon the level of RD&D investments coming in this area, which in turn would depend upon the signals sent by global GHG mitigation regimes (IPCC 2007).

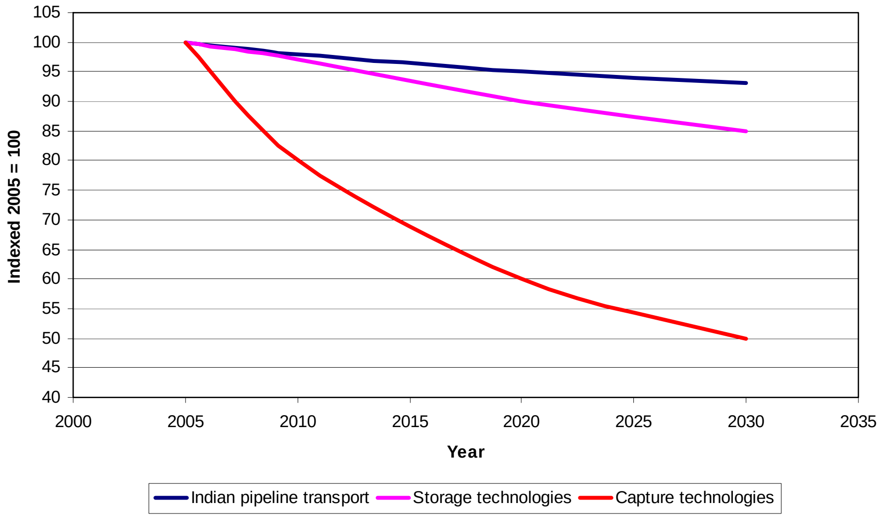


Figure 2.13 Future cost development of capture, transport & storage technologies. *Sources:* Expert judgement and based on Dooley et al., 2004; Friedmann et al., 2006; Riahi et al., 2004 ; Wildenborg et al., 2004; IEA, 2005; IPCC, 2007; and Christensen et al., 2006.

2.4.4.5 Conclusion

CCS has moved centre-stage in the last 5-6 years as a major alternative for large scale CO_2 emission mitigation. However CCS is currently associated with around a 25% energy penalty due to the additional energy required for capture, transport and storage of CO_2. This increases the costs of CCS. Capture cost reduction is the technological crux as it contributes around 60-80% to the CCS system chain costs, especially for penetrating the Indian markets (Shahi 2007). Many research initiatives are currently ongoing globally in this direction. Finding better and more energy efficient adsorbents is a focus area for research. Global research thrust is gradually moving to pre-combustion capture with potentially higher cost reduction possibilities.

This study has estimated the CO_2 capture and storage costs for global and Indian conditions and made an approximation of future cost developments. Although much technical data exists on the global level, data for Indian conditions is still limited. Therefore the estimates made in this report should only be seen as an initial investigation of Indian CCS costs on which to build future studies.

2.5 REFERENCES

Azar, C., Lindgren, K., Larson, E., Mollersten, K. (2006). Carbon capture and storage from fossil fuels and biomass – Costs and potential role in stabilizing the atmosphere, Springer Netherlands.

Bachu, S., Bonijoly, D., Bradshaw, J., Burruss, R., Holloway, S., Christensen, N-P. & Mathiassen, O-M. 2007. CO_2 storage capacity estimation: Methodology and gaps. *International Journal of Greenhouse Gas Control*, **1**, 430-443.

Biswas Subhashis, Niladri Chakraborty, Pinaki Sarkar, Joshi George and Ashim Chaudhary (2004). GHG Emission Measurements from Coal Combustion in Selected Industries. In: Mitra A.P, Subodh Sharma, Sumana Bhattacharya, Amit Garg, Sukumar Devotta and

Kalyan Sen, Climate Change and India- Uncertainty Reduction in Greenhouse Gas Inventory Estimates. University Press, Hyderabad.

Bromhal, G.S., Sams, N.W., Jikich, S., Ertekin, T. & Smith, D.H. 2005. Simulation of CO_2 sequestration in coal beds: The effects of sorption isotherms. *Chemical Geology* **217**(3-4): 201-211.

Chaudhary, S. K., (2000) *Coal in India*. World Energy Congress.

Christensen, J., Denton, F., Garg, A., Kamel, S., Pacudan, R., Usher, E. (2006). Changing Climates The Role of Renewable Energy in a Carbon-Constrained World, REN21.

Cleantech. The Indian Cement Industry - A Perspective of Environment Friendliness. http://www.wbcsdcement.org/pdf/tf5/cement-india.pdf

CMA, 2006. Cement Manufactures Association, http://www.cmaindia.org/

CMIE, 2005. Energy 2005, Economic Intelligence Service, Centre for Monitoring of Indian Economy, Mumbai.

Dhar, S. (2006). Gas markets in India. Presentation made at the "Balancing Energy, Development and Climate Policies in India" workshop, New Delhi, 30 Nov.

Dooley, J.J., Dahowski, R.T., Davidson, C.L., Bachu, S., Gupta, N. & Gale, J. (2004). A CO_2 storage supply curve for North America and its implications for the deployment of carbon dioxide capture and storage systems. In: Proceedings of 7th International Conference on Greenhouse Gas Control Technologies. Vol. 1, Peer-reviewed papers and plenary presentations, IEA Greenhouse Gas Programme, Cheltenham, UK; 2004, IEA, Paris, France.

Dutt, A. B., Mukhopadhyay, A. and Chakrabarti, N. C., (1999) Coal bed methane potentials in Central Indian coalfields-possibilities and prospects, Proc. Int. Sem.Coal Bed Methane Prospects and Potentialities, December, pp.26-35.

EWEA/Greenpeace (2004). Wind Force 12 – May 2004 Report.

Friedmann, S. J., Dooley, J. J., Held, H. and Edenhofer, O. (2006). The low cost of geological assessment for underground CO_2 storage: Policy and economic implications. *Energy Conversion and Management*, **47** (13-14), 1894-1901.

Garg, A. and Shukla P. R. 2002. Emissions Inventory of India. Tata McGraw-Hill Publishing Company Limited, New Delhi.

Garg, A., Deepa Menon, Manmohan Kapshe and P. R. Shukla (2004). Carbon Dioxide Capture and Storage Potential in India, in E.S. Rubin, D.W. Keith and C.F. Gilboy (eds.), *Proceedings of 7th International Conference on Greenhouse Gas Control Technologies.* Volume 1: Peer-Reviewed Papers and Plenary Presentations, IEA Greenhouse Gas Programme, Cheltenham, UK.

Garg, A., Shukla, P. R. and Kapshe, M. 2002. Large Point Source (LPS) Emissions from India: Regional and Sectoral Analysis. Atmospheric Environment 36, 213

GHG protocol, GHG emission Claculation tools on GHG Protocol web site http://www.ghgprotocol.org/

GOI, 2001. Report by the Working Group on the Fertilizer Industry for the XI Five Year Plan (2007-12).

GOI, 2007. Annual report 2006-07, Department of Fertilisers, Ministry of Chemical and Fertiliser, Government of India. http://fert.nic.in/annualreport/annual-report0607-english.pdf

GSI (Geological Survey of India) 2007. Coal Resources of India 2007.

Haddadji, R. (2006). The In-Salah CCS experience, Sonatrach Algeria, presentation.

Hansen, T. B. (2007). Personal communication.

Heddle, G., Herzog, H., Klett, M. (2003). The Economics of CO_2 Storage, MIT Laboratory for Energy and the Environment.

ICRA, 2006. The Indian Cement Industry, Sector Analysis, ICRA.

http://www.icra.in/recentrel/Cement-200607.pdf

IEA (2005). Prospects for Hydrogen and Fuel Cells, IEA Energy Technology Analysis.

IEAGHG, 2004. IEAGHG CO_2 sources database 2004.

IPCC (Intergovernmental Panel on Climate Change), 2005: *Special Report on Carbon Dioxide Capture and Storage*, Metz, B., O. Davidson, L. Meyer and H.C. de Coninck (eds.), Cambridge University Press, Cambridge, United Kingdom, 440 pp.

IPCC, 2006. IPCC Guidelines for National Greenhouse Gas Inventories-2006

IPCC (2007), Fourth Assessment Report, Contributions of WG-3.

Intergovernmental Panel on Climate Change. Kapshe, M., A. Garg and P.R. Shukla 2003. Application of AIM/Local Model to India using Area and Large Point Sources. In Climate Policy Assessment: Asia-Pacific Integrated Modelling (Eds.) Kainuma, M., Matsuoka, Y. and Morita, T. Springer-Verlag, Tokyo, Japan.

Kumar, M. S., Roy, K. K. and Gyani, O. N., 2007. A study on application of CO_2 EOR in a mature oil field. Paper presented at the International workshop on R&D challenges in carbon capture and storage technology for sustainable energy future. Hyderabad, India, January 12-13, 2007.

Larsen, J.W. 2003. The effects of dissolved CO2 on coal structure and properties. *International Journal of Coal Geology*, **57**, 63-70.

Mining Geological and Metallurgical Institute of India (2006). *Indian Mining Directory, 6th Edition,* January, pp.8-29.

Mondal, A. 2006. Gondwana Basins in India – Vast Geologic Storage Sites for CO_2 Injection. *Proceedings of the International Workshop on R&D Challenges in Carbon Capture & Storage Technology for Sustainable Energy Future (IWCCS-07)*,12-13 January 2007. National Geophysical Research Institute, Hyderabad.

MoPNG, 2005. Basic Statistics 2004-05, Ministry of Petroleum and Natural Gas, Government of India.

Reeves, S.R. and Schoeling, L. 2001. Geological sequestration of CO_2 in coal seams: reservoir mechanisms, field performance and economics. In *Proceedings of the 5th International Conference on Greenhouse Gas Control Technologies* (ed. D. Williams B. Durie, P. McMullan, C. Paulson & A.Smith), Collingwood, Australia: CSIRO, pp.593-598..

Riahi, K., Rubin, E. S., and Schrattenholzer, L. (2004). Prospects for carbon capture and sequestration technologies assuming their technological learning. Energy, **29** (9-10), 1309-1318.

Schroeder, K., Ozdemir, E., & Morsi, B.I.. Sequestration of carbon dioxide in coal seams. Proceedings of the First National Conference on Carbon Sequestration. NETL. 2001. http://www.netl.doe.gov/publications/proceedings/01/carbon_seq/3a4.pdf

Shahi, R. V. (2007). Keynote address: International workshop on R&D challenges in carbon capture and storage technology for sustainable energy future. Hyderabad, India, January 12-13, 2007.

Sharma T.C and O. Coutinho, 1992. Economic and Commercial Geography of India. Vikas Publishing House, Delhi, India.

Shi, J-Q. and Durucan, S. 2005. A numerical simulation study of the Allison Unit CO_2-ECBM pilot: the effect of matrix shrinkage and swelling on ECBM production and CO_2 injectivity. In: Rubin, E.S., Keith, D.W. & Gilboy, C.F. (eds.), *Proceedings of 7th International Conference on Greenhouse Gas Control Technologies*. Vol. 1: Peer-reviewed papers and plenary presentations, Elsevier, pp. 4391-439.

Singh, A.J., Mendhe, V.A. & Garg, A. 2006. CO_2 sequestration potential of geologic formations in India. *Proceedings of the 8th International Conference on Greenhouse Gas Control Technologies*, Trondheim, Norway, 19-22 June, 2006, ISBN: 0-08-046407-6, Elsevier, published on CD.

Sonde, R. R. (2006), Trends, Issues and Challenges in the Electricity Market – clean coal technologies, presentation.

Sonde, R. R. (2007). R&D challenges in carbon capture and storage technology for sustainable energy future. Paper presented at the International workshop on R&D challenges in carbon capture and storage technology for sustainable energy future. Hyderabad, India, January 12-13, 2007.

TEDDY, 2005. TERI Energy Data Directory & Yearbook 2004-05. The Energy and Resources Institute, New Delhi, India.

Varma, S. K., (1999) A case of riverine transport of coal and the other clean coal options, Int. Symp. Clean Coal Initiatives, New Delhi, pp375-396.

Verma, A. K. and Mazumdar, S., (1999) Cleat pattern and petrographic investigations of some coal seams in Jharia coalfield, India for coal bed methane. International Seminar Coal Bed Methane Prospects and Potentialities, December, pp.131-140.

Wildenborg T, Gale J, Hendricks C, Holloway S, Brandsama B, Kreft E, Lockhorst A. (2004). Cost curves for CO_2 storage: European sector. In: Proceedings of 7th international conference on greenhouse gas control technologies. Vol. 1: peer-reviewed papers and plenary presentations, IEA greenhouse gas programme, Cheltenham, UK, 2004, IEA, Paris, France.

World Bank (2007). Thermal Power Conversion Technologies, online 27.04.07 at http://www.worldbank.org/html/fpd/em/power/EA/mitigatn/thermpow.stm#atpp.

World Resources Institute 1998-9. *World Resources- A guide to the global environment.* A joint publication by The World Resource Institute, The United Nations Environment Programme, The United Nations Development Programme, The World Bank, Oxford University Press, 369 pp.

Zhang, C.J., Smith, M., McCoy, B.J. 1993. *Kinetics of Supercritical Fluid Extraction of Coal: Physical and Chemical Processes.* In: Kiran, E., Brennecke, J.F. (eds.), Supercritical Fluid Engineering Science: Fundamentals and Applications. American Chemical Society, Washington DC, pp. 363-379.

3 Pakistan

3.1 CO_2 SOURCES IN PAKISTAN

3.1.1 Introduction

Greenhouse gas (GHG) emissions in Pakistan have been documented in some detail in studies including: Hagler Bailly Pakistan's (HBP) "National Greenhouse Gas Emissions and Sinks Study" in 1996; The Asian Development Bank's (ADB) "The Asia Least-cost Greenhouse Gas Abatement Strategy (ALGAS)" in 1998; The Ministry of Environment's (MoE) "Pakistan's Initial National Communication on Climate Change" in November 2003. Total CO_2 emissions in Pakistan in 2004 were 1255.67 million tonnes in 2004 (United Nations Statistical Division 2007).

HBP's study includes a detailed GHG inventory and GHG mitigation policy options. The ADB ALGAS project studied national GHG emissions and prepared a detailed analysis of GHG abatement options in conjunction with national development objectives. The MoE's initial communication document identifies sources and sinks of direct and indirect GHGs, and supplies emissions figures for various sectors.

In this study, emissions data from various industrial processes and their associated emissions factors are used to produce estimated carbon dioxide (CO_2) emissions figures, on a plant-wise basis. This data has been used to update the IEAGHG R&D programme's CO_2 sources inventory for Pakistan. The largest constraint is a general dearth of plant-level information. Plant-wise production figures are not usually available; accessible statistics tend to only provide total production. As required by the database, lat/long coordinates to an accuracy of up to two decimal places have been provided for CO_2 point sources. While there is scope for increasing accuracy, maps with more precise coordinates are unavailable.

Total CO_2 emissions recorded from large point sources in the updated database are 45 million tonnes per annum.

3.1.2 Sectors

Plant-wise data for the following sectors has been updated in the IEAGHG CO_2 sources inventory:

- Ammonia (fertilizer plants)
- Cement
- Ethanol
- Iron and steel
- Gas processing
- Power
- Refineries

3.1.2.1 AMMONIA (FERTILIZER PLANTS)

Urea is the most commonly produced fertilizer in Pakistan. It has not proved possible to calculate emissions factors for other fertilizers; however it is safe to assume that their contribution to CO_2 emissions is negligible as they are produced in much smaller quantities, and are mostly imported (Table 3.1).

Table 3.1 Types of fertilizer produced in Pakistan (2004)

Company name	City	Urea	DAP	MAP	CAN	AS	NP	SSP 16%	SSP 18%	NPK
Dawood Hercules	Near Sheikhupura	x	Imported							
Engro	Dist. Daharki, Ghotki	x	Imported							
Engro	Port Qasim Karachi		Imported	Imported						x
NFC Pak-Arab	Multan	x			x					
NFC Pak-American	Iskanderabad, Daudkhel	x	Imported			x				
NFC Pak-China		NoProd	Imported							
NFC Lyallpur Chemicals & Fertilizers (Pvt.) Ltd.	Faisalabad		Imported						NoProd	
NFC Lyall Chemicals & Fertilizer (Pvt.) Ltd.	Jaranwalla		Imported						x	
NFC Hazara Phosphate Fertilizers (Pvt.) Ltd.	Haripur		Imported					NoProd	x	
FFC	Goth Machhi, dist. Rahim Yar Khan	x	x							
FFC	Mirpur Mathelo, Dist. Ghotki	NoProd								
FFC-Jordan Fertilizer Co. Ltd.		x	x							
FFBL	Bin-Qasim Karachi	x	x							

DAP: Diammonium Phosphate; MAP: Monoammonium Phosphate, CAN: Calcium Ammonium Nitrate; AS: Ammonium Sulphate; NP: Nitrogen Phosphate; SSP: Single Super Phosphate, NPK: Nitrogen, Potassium, Phosphorous.

NoProd: No production in 2004

Available statistics do not always show the amount of ammonia used in the production of fertilizer in Pakistan (or the installed ammonia production capacity). Wherever this was the case, plant-wise data for fertilizer production was obtained and a conversion factor with which the amount of ammonia originally used can be derived was calculated. The procedure was as follows:

Thirty-four molecules of ammonia are required to produce 60 molecules of urea. The conversion factor is therefore 34/60. Multiplying this factor by any amount in kilotonnes of urea will yield the amount of ammonia consumed to produce that amount of urea.

Finally, using an emissions factor, one can procure an estimated figure for CO_2 emissions from that plant. Below is a list of assumptions and constraints:

- It was assumed all fertilizer plants run at full capacity 365 days a year (this generally is the case with fertilizer plants).
- All figures used are from the period 2003–2004 to maintain consistency.
- The emissions factor 0.74 Kg of CO_2 per Kg of Ammonia has been taken from an ammonia entry for Pakistan from the IEA GHG database to derive Pakistan-specific estimates. Where a plant produces both urea and another fertilizer, and ammonia production is not specified by the company, ammonia capacity has been calculated using only urea production figures.
- Where there is a difference between installed ammonia capacity and calculated ammonia capacity, the larger figure was used for calculating the final CO_2 emission level.
- Ammonia capacity is calculated from actual or installed urea production, whichever is available. There were no instances where both were available.

3.1.2.2 Cement

With over 20 plants in operation at any given time, scattered mainly over the Punjab and Sindh, Pakistan's cement industry produces 15.15 million tonnes of cement (FBS, 2006). As in the rest of the world, Pakistan mainly produces Portland cement.

For the Pakistan cement industry update, the IPCC standard CO_2 emissions factor for clinker production has been used, assuming the following:

- The fraction of lime (CaO) used in the clinker is approximately 64.6% (IPCC, 1996)
- The molecular weight ratio of CO_2/CaO is 0.785

When multiplied, these figures give the final emission factor for clinker, 0.5071 tonnes of CO_2 per tonne of clinker.

3.1.2.3 Ethanol

Ethanol had not been accounted for in the Pakistan portion of the previous IEAGHG database. However, the demand for industrial alcohol and ethanol as an alternative fuel has increased in the EU (among the largest importers of Pakistan's ethanol) in recent years. Pakistan now operates 17 distilleries (three in the North-West Frontier Province, seven in the Punjab, and seven in Sindh) with capacities ranging from 3.5 to 42 million litres a year (capacity figures have been used in the database calculations due to the absence of production data). An emission factor of 0.799 gigagrams of CO_2 per million litres is used in the database. This figure has been taken from the database for the US and Canada. Pakistan's distilleries are fairly small, and the individual CO_2 emissions do not therefore exceed 34 Gg.

3.1.2.4 Iron and Steel

Pakistan has only one steel mill that actually manufactures iron products from iron ore. This facility is Pakistan Steel Mills (PSM) in Karachi, Sindh. Its products include billets, rolled products, and galvanized products. The emissions factor used is 1.27 Kg of CO_2 per Kg of steel produced.

Plant-wise production data for steel melting and re-rolling mills in Pakistan was not available so they were excluded from the database. Their total emissions are however shown in Table 3.2. These facilities either purchase steel from PSM, or import it.

Table 3.2 Total steel industry emissions (2005–06)

Steel industry	Year	No. of facilities*	Total production	Emissions factor (Kg CO_2/Kg steel)	CO_2 emissions (t)
Steel melting	July '05–Nov '06	168	1,416,647	1.27	1,799,141.69
Steel re-rolling	July '05–Nov '06	300	1,378,570	1.27	1,750,783.90

* Estimated figure

Source (production figures and number of facilities): Ministry of Industries and Production (MoIP) 2007

3.1.2.5 Gas processing

Pakistan possesses significant natural gas reserves. According to the Hydrocarbon Institute of Pakistan (HDIP), Pakistan's recoverable reserves stand at 32.8 trillion cubic feet (TCF).

It was not possible to locate a suitable emissions factor for gas processing in Pakistan, and therefore we are unable to provide figures for CO_2 emissions. Production figures in thousand cubic metres per year (Mm^3/a) have however, been provided for the future.

3.1.2.6 Power

Pakistan's power plants are owned and operated by the Water and Power Development Authority (WAPDA), the Karachi Electric Supply Corporation (KESC), and various independent power producers (IPPs). The technology utilized is steam turbo-generators and simple and combined gas turbines. Indigenous gas and coal are the primary fuels, but furnace oil (FO) and high-speed diesel (HSD) oil are also used.

Only fossil fuel fired power plants have been included in this section; hydro-power plants generate a large portion of Pakistan's electric power. The vast majority of fossil fuel fired power plants in Pakistan utilize natural gas. Oil is a close second, and coal is used in only one location, the fluidised bed combustion (FBC) plant in Lakhra in district Dadu, Sindh. The emission factors for the various fuels are shown in Table 3.3.

Table 3.3 Emission factors by fuel type

Fuel type	Natural gas	FO	HSD oil	Coal
Emission factor (Kg CO_2/KWh)	400	500	500	1000

Source: IEA GHG CO_2 emissions database v. 2006

Power plants typically comprise several 'units' that produce electricity, burning different fossil fuels. Where a unit generates power utilizing dual-fuel combustion, the power produced in GWh by each type of fuel have been separated, and the relevant emissions factor used.

Table 3.4. below summarises the fuel types used in Pakistan's power plants. Natural gas is the most widely used fuel.

Table 3.4 Fuel types used in Pakistan's power plants

Power plant	**Fuel**			
	Natural gas	FO	HSD oil	Coal
GTPS Shahdra	x			
SPS Faisalabad	x	x		
GTPS Faisalabad	x		x	
NGPS Multan	x	x		
TPS Multan Cantt.	-	-	-	-
TPS Muzaffar Garh	x	x		
TPS Guddu (Units 1-4)	x	x		
TPS Guddu (Units 5-13)	x			
TPS Sukkur	-	-	-	-
GTPS Kotri	x			
TPS Jamshoro	x	x		
FBC Lakhra				x
TPS Quetta	x			
GTPS Panjgur			x	
TPS Pasni			x	
TPS Korangi	x	x		
GTPS Korangi Town	x		x	
GTPS Site	x		x	
TPS Bin Qasim	x	x	x	
AES Lalpur		x		
AES Pak Gen		x		
Altern Energy	x			
Fauji Kabirwala	x			
Gul Ahmed		x		
Habibullah	x		x	
HUBCO		x		

Japan Power		x	
KAPCO	x	x	x
Kohinoor Energy		x	
Rousch Power	x		x
Saba Power		x	
Southern Electric		x	x
Tapal Energy		x	
TNB Liberty Power	x		
Uch Power	x		x

Source: HDIP, 2005

Figure 3.1 shows the CO_2 emissions of some of Pakistan's larger power plants.

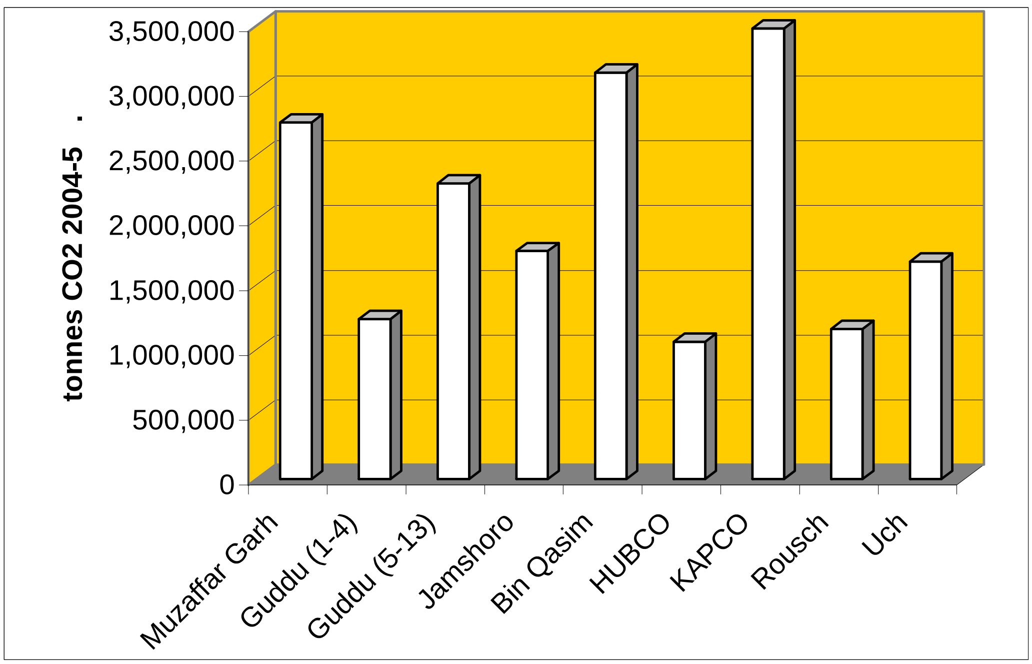


Figure 3.1 CO_2 emissions of large power plants (2004-05)

3.1.2.7 REFINERIES

Pakistan possesses six oil refineries of varying capacities. Figure 3.2 shows their individual production and CO_2 emissions for 2005.

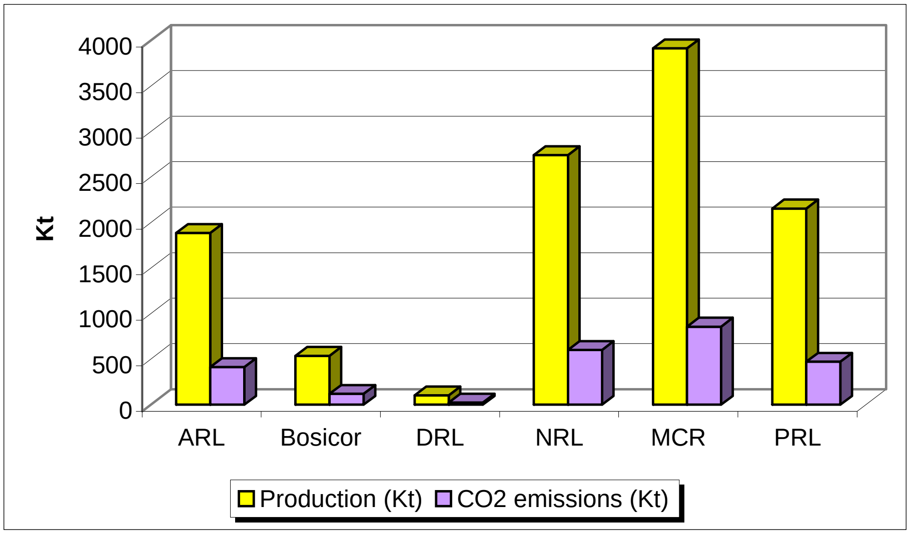


Figure 3.2 Refineries production and emissions (2005)

ARL: Attock Refinery Limited; DRL: Dhodak Refinery Ltd.; NRL: National Refinery Ltd.; MCR: Mid-Country Refinery; PRL: Pakistan Refinery Ltd.

3.1.3 Emissions mapping

Table 3.5 below shows the estimated figures for CO_2 emissions broken down by province, and further by cities and districts. It must be noted that these figures are based on immobile sources of CO_2 that have been collected for the sectors included in this database only (ammonia, cement, ethanol, steel, power, and refineries).

Table 3.5 Estimated CO_2 emissions of selected sectors by city/district

Province	City/district	Emissions from	Approx. emissions (t)	Provincial total (10^6 t CO_2)
Balochistan	Dera Murad Jamali	Power	1,677,810	3.17
	Hub	Power	1,059,000	
	Panjgur	Power	985	
	Pasni	Power	930	
	Quetta	Power	427,026	
	Sub Tehsil Gadani, District Lasbella	Refineries	118	
Sindh	Dhabeji, D eh D hando Dhabeji	Cement	380	22.61
	Dist. Dadu	Power	1,934,610	
	Ghotki	Ammonia	359	
	Hyderabad	Power, cement	174	
	Kalo Kahar, Nooriabad	Cement	484	

	Karachi	Power, cement, ethanol, refineries, ammonia, iron and steel	4,747,123	
	Kashmore, dist. Jacobabad	Power	3,517,014	
	Kotri	Power	322,008	
	Mirpur Mathelo, District Ghotki	Ammonia	295	
	Sakkran. Hub Chowki, Lasbela district	Cement	365	
	Sukkur	Power, cement	517,568	
	Thatta	Cement	152	
The Punjab	Babri Banda	Cement	273	**17.06**
	Chenki	Cement	304	
	Dist. Chakwal	Cement	273	
	Dist. Dera Gazi Khan	Cement, refineries	858	
	Dist. Muzaffargarh	Power, refineries	3,384,222	
	Faisalabad	Power, ethanol, ammonia	544,214	
	Farouka	Power	297,585	
	Goth Machhi, district Rahimyar Khan	Ammonia	588.818	
	Iskanderabad, Dist. Mianwali	Cement, ammonia	871	
	Jhang	Ethanol	32	
	Kabirwalla	Power	433,580	
	Kot Addu	Power	3,477,120	
	Lahore	Power, cement, ethanol	651,901	
	Morgah, Rawalpindi	Refineries	413	
	Multan	Ammonia	51	
	Near Sheikhupura	Ammonia	220	
	Nizampur	Cement	609	
	Pind Dadan Khan	Cement	243	
	Piranghaib, near Multan	Power	176,980	
	Sidhnai Barrage	Power	1,158,620	

	Tehsil Fateh Jang, District Attock	Power, cement	4,312	
	Wah	Cement	456	
NWFP	Haripur dist.	Cement, ammonia	274	**1.31**
	Mardan	Ethanol	12	
	Nowshera	Cement	380	
	Peshawar	Ethanol	5	
	Pezu, distt. Lakki Marwat	Cement	637	
Federal territory	Sangjani, district Islamabad	Cement	304	**0.3**

As the table shows, Sindh is responsible for over 22 million tonnes of CO_2 emissions, followed by the Punjab at over 17 million tonnes, then Balochistan and the North-west Frontier Province (NWFP).

Figure 3.3 shows the locations of CO_2 sources in Pakistan.

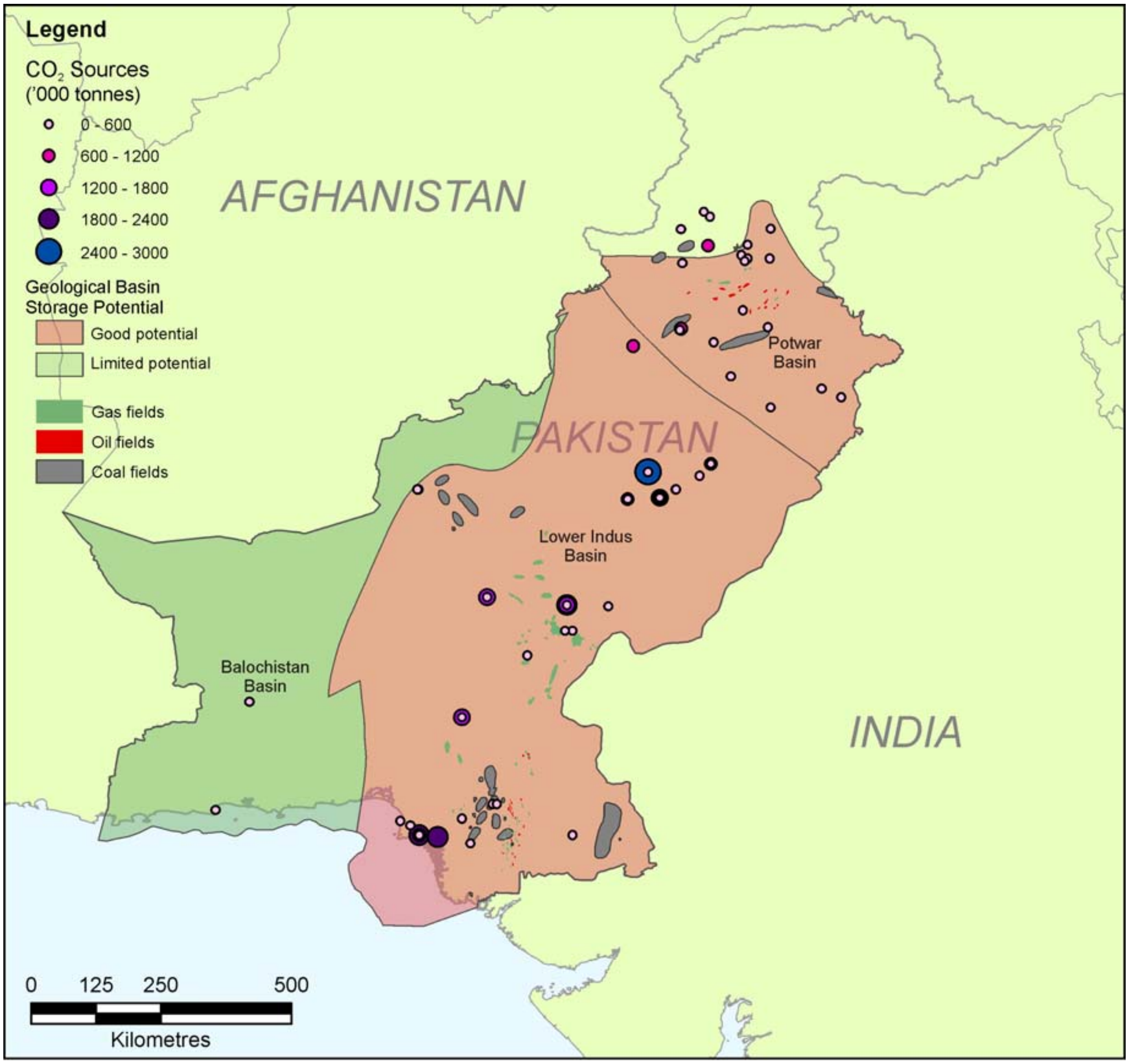


Figure 3.3 Location of CO_2 point sources and potential geological storage sites in Pakistan

3.2 POTENTIAL GEOLOGICAL CO_2 STORAGE SITES IN PAKISTAN

3.2.1 Estimated CO_2 storage capacity in oil and gas fields in Pakistan

Up to 1997 about 431 exploratory wells had been drilled in Pakistan, resulting in 115 discoveries, 51 of oil and 64 of gas and condensate. However, the oil fields are small and their production ranges from less than 50 to about 18000 barrels per day. Four giant gas fields (Sui, Mari, Uch and Qadipur) and two majors (Pir Koh and Khairpur) have been discovered.

According to Raza (1997) total petroleum and natural gas reserves in Pakistan are estimated to be about 0.6 billion US barrels and 31.0 tcf respectively. Recently a large gas field has been discovered at Bhit in the Kirthar Piedmont zone and the prospects are that it will turn out to be a major (Aslam 1997).

The location of oil and gas fields in Pakistan is shown in Figure 3.3. Tables 3.6 and 3.7 show the estimated CO_2 storage capacity of the oil and gas fields of Pakistan, based on reserves data given in Kazmi & Jan (1997).

Table 3.6 Estimated CO_2 storage capacity of oil fields in Pakistan

Field	Original Recoverable Reserves million US barrels	ORR 10^6 m^3	FVF (default = 1.2)	CO_2 density reservoir conditions (default = 0.6 t m^{-3})	Estimated CO_2 storage capacity 10^6 tonnes
Dhurnal	50.9	8.1	1.2	0.6	3.79
Meyal	42.5	6.8	1.2	0.6	3.16
Dhulian	41.4	6.6	1.2	0.6	3.08
Missakaswai	34.7	5.5	1.2	0.6	2.58
Balkassar 2)	34.0	5.4	1.2	0.6	2.53
Fimkassar	30.0	4.8	1.2	0.6	2.23
Laghari	20.3	3.2	1.2	0.6	1.51
Tando Alam	20.2	3.2	1.2	0.6	1.50
Dhodak (c)	16.2	2.6	1.2	0.6	1.20
Toot	15.8	2.5	1.2	0.6	1.17
Mazari	14.7	2.3	1.2	0.6	1.10
Kunar	14.0	2.2	1.2	0.6	1.04
Dakhni (c)	12.4	2.0	1.2	0.6	0.93
Ratana (c)	12.0	1.9	1.2	0.6	0.89
Thora	11.2	1.8	1.2	0.6	0.83
South Mazari	10.9	1.7	1.2	0.6	0.81
Joyamair	10.5	1.7	1.2	0.6	0.78
Adhi (c)	10.2	1.6	1.2	0.6	0.76
Bobi (c)	9.8	1.6	1.2	0.6	0.73
Pasakhi	9.4	1.5	1.2	0.6	0.70
Sono	8.7	1.4	1.2	0.6	0.64
Khaskheli	8.2	1.3	1.2	0.6	0.61
Liari	5.4	0.9	1.2	0.6	0.40
Lashari Centre	5.3	0.8	1.2	0.6	0.39
Chak-Naurang	4.7	0.7	1.2	0.6	0.35
Dabhi	4.4	0.7	1.2	0.6	0.33
Khaur	4.3	0.7	1.2	0.6	0.32
Bari	2.5	0.4	1.2	0.6	0.19
Bhangali	1.8	0.3	1.2	0.6	0.14
Bukhari	1.7	0.3	1.2	0.6	0.12
North Akri	1.5	0.2	1.2	0.6	0.11
Dhamraki	1.4	0.2	1.2	0.6	0.10
Turk and Turl Deep (c)	1.3	0.2	1.2	0.6	0.10
Sonro (c)	1.0	0.2	1.2	0.6	0.07
Ghungro	0.8	0.1	1.2	0.6	0.06
Sadkal (c)	0.7	0.1	1.2	0.6	0.05
Khorewah	0.7	0.1	1.2	0.6	0.05
Bhatti (c)	0.6	0.1	1.2	0.6	0.05
Tajedi	0.5	0.1	1.2	0.6	0.03
Halipota	0.4	0.1	1.2	0.6	0.03
Ghotana	0.4	0.1	1.2	0.6	0.03
Nari	0.4	0.1	1.2	0.6	0.03
Matli	0.3	0.0	1.2	0.6	0.02

Daru	0.3	0.0	1.2	0.6	0.02
Mukhdumpur	0.2	0.0	1.2	0.6	0.02
Lashari South (c)	0.2	0.0	1.2	0.6	0.02
Buzdar North (c)	0.2	0.0	1.2	0.6	0.02
Mahi	0.2	0.0	1.2	0.6	0.02
Bhal Syedan (c)	0.2	0.0	1.2	0.6	0.01
Paniro	0.2	0.0	1.2	0.6	0.01
Golarchi (c)	0.2	0.0	1.2	0.6	0.01
Koli (c)	0.2	0.0	1.2	0.6	0.01
Kato	0.1	0.0	1.2	0.6	0.01
Duphri	0.1	0.0	1.2	0.6	0.01
Buzdar (c)	0.1	0.0	1.2	0.6	0.01
Rind (c)	0.1	0.0	1.2	0.6	0.00
Total	480.5	76.4			35.73

Table 3.7 Estimated CO_2 storage capacity of gas fields in Pakistan

Gas field	Original Recoverable Reserves 10^9 m^3	Default Gas Expansion Factor	Estimated CO_2 density t m^{-3} (default = 0.6	Estimated CO_2 storage capacity 10^6 tonnes
Sui	244.2	200	0.60	476.3
Mari	178.4	200	0.60	347.9
Uch	114.7	200	0.60	223.7
Qadirpur	112.7	200	0.60	219.7
Pirkoh	51.0	200	0.60	99.4
Khairpur	28.3	200	0.60	55.2
Kandhkot	22.2	200	0.60	43.2
Kadanwari	20.6	200	0.60	40.2
Dhodak	16.5	200	0.60	32.1
Ratana	9.9	200	0.60	19.3
Nandpur	8.4	200	0.60	16.3
Loti	7.8	200	0.60	15.3
Dakhni	7.2	200	0.60	14.1
Adhi	3.3	200	0.60	6.4
Turk	3.2	200	0.60	6.3
Zin	2.8	200	0.60	5.5
Khorewah	2.8	200	0.60	5.5
Jandran	2.3	200	0.60	4.5
Bukhari	1.9	200	0.60	3.8
Hundi	1.7	200	0.60	3.3
Matli	1.6	200	0.60	3.1
Golarchi	1.6	200	0.60	3.1
Bobi	1.2	200	0.60	2.3
Sari	1.1	200	0.60	2.2
Bhatti	1.0	200	0.60	1.9
Panjpir	0.9	200	0.60	1.9
Turk Deep	0.9	200	0.60	1.8

Nakurji	0.7	200	0.60	1.4
Mukhdumpur	0.7	200	0.60	1.3
Mazarani	0.5	200	0.60	1.0
Sonro	0.5	200	0.60	1.0
Dabhi	0.5	200	0.60	0.9
Koli	0.4	200	0.60	0.8
Mahi	0.4	200	0.60	0.7
Daru	0.4	200	0.60	0.7
Rodho	0.4	200	0.60	0.7
Kothar	0.3	200	0.60	0.7
Buzdar	0.2	200	0.60	0.4
Nari	0.2	200	0.60	0.4
Nur	0.2	200	0.60	0.3
Kato	0.1	200	0.60	0.3
Tanda Ghulam Ali	0.1	200	0.60	0.2
Dabhi South	0.1	200	0.60	0.2
Bhal Syeden	0.1	200	0.60	0.2
Jabo	0.1	200	0.60	0.2
Halipota	0.1	200	0.60	0.1
Rind	0.0	200	0.60	0.1
Pir	0.0	200	0.60	0.1
Totals	854.4			1666.0

Thus the total storage capacity in oil and gas fields in Pakistan is estimated to be approximately 1.7 Gt CO_2. However none of the oil fields are thought to have a storage capacity of 10 Mt or more and thus none of them have any significant storage capacity. Thirteen of the gas fields are thought to have a storage capacity of 10 Mt or more – their combined storage capacity is estimated to be approximately 1.6 Gt CO_2. Four gas fields (the Sui, Mari, Qadirpur and Uch fields) are estimated to have the potential to store >200 Mt CO_2.

3.2.2 Potential for CO_2 storage in coalfields in Pakistan

The following description of the coalfields of Pakistan is abstracted from Kazmi & Jan (1997). Coal mainly occurs in Palaeocene and Eocene rocks, though there is one occurrence in Late Permian rocks of the Salt range, and coal deposits that have been transformed into graphite have been reported from the Permian sequence near Reshit (Chapursan Valley) north of Hunza. The location of coalfields in Pakistan is shown in Figure 3.3.

The Indus Basin contains three main coal-bearing regions:

3.2.2.1 The Kohat-Potwar coal region

This lies in the northern part of the Indus Basin. It contains two coalfields:

The Makarwal coalfield covers an area of about 75 km^2 and is located 45 km SW of Kalabargh (32º 58', 71º 34'). Coal crops out in an elongate anticline with a steep overturned eastern limb and 15º to 50º dip on its western limb. A number of faults affect the coalfield and cause difficulties in mining. The main coal seam occurs at the base of the Hangu Formation and varies from 0.3 to 3.0 m in thickness, with an average thickness of about 1.1 m (Warwick & Hussein 1990). Annual output is c. 25000 tonnes. Coal resources are estimated at 22 million tonnes. The coal is of high volatile B and C bituminous rank.

The Salt Range coalfield covers an area of approximately 1500 km^2 in the central and eastern Salt Range. The northern limit of the coalfield is marked by the approximate areal extent of the Eocene limestones (Warwick & Hussein 1990). The coal occurs in the Patala Formation in a synclinal plateau bounded by erosional anticlines. A number of normal faults traverse the area forming small escarpments. They cause repetition of the exposures of the Patala Formation, which could be mined for coal. There are more than 2 seams in the Salt Range but in most cases only one is mineable.

The maximum thickness of the mineable coal seam is about 2.13 m. Its rank ranges from high-volatile bituminous C to B. Annual production of coal is about 225,000 tonnes and coal resources are estimated to be about 235 million tonnes.

Minor coal occurrences are found in Kohat-Potwar region in the Hangu-Karak area in a series of steeply dipping EW-trending parallel folds which plunge to the east. The coal occurs in the Hangu Formation. It is likely to be a continuation of the Makarwal coalfield. Coal is being mined on a limited scale. Annual coal production from this area is about 26,500 tonnes.

Minor production also occurs in the Cherat area where coal occurs in the folded Patala Formation. Exposed coal beds are about 1 m in thickness. At least a limited extent is indicated by boreholes. Limited data indicate that the coal has a calorific value of 13000 BTU, it contains 3% ash and 0.5% sulphur. Annual production from Cherat is about 500 tonnes.

Minor production also occurs in the Kotli area, where the Patala formation contains two coal beds. The lower bed occurs immediately above the unconformity between Cambrian dolomite and the Palaeocene strata. The thickness of these beds ranges from 0.02 to 2.2 m, average 0.6 m. The coal grades laterally into carbonaceous shale. On average the coal contains 27.94% ash, 48.4% fixed carbon and 2.14% sulphur. Recoverable reserves are estimated at 61,000 tonnes.

3.2.2.2 THE QUETTA – HARNAI – DUKI COAL REGION

This is in NE Balochistan. It covers an area of approximately 12,500 km^2 and extends westwards for about 240 km from near Bahlol. (30º 01’, 69º 28’) to Quetta and then another 160 km southwards to Johan (29º 20’, 66º 52’). In the Quetta-Harnai-Duki region, coal occurs in the Ghazij Group of Lower Eocene age. Coal is mainly mined in the Sor Range-Deghari, Pir Ismail Ziarat, Mach, Khost-Harnai and Duki areas. Coal also occurs at in the Chamalong-Bahlol area, east of Duki and near Johan.

The Sor Range-Deghari coalfield is located about 10 km east and southeast of Quetta and comprises a NW-SE-trending syncline. A number of coal mines are clustered along its eastern limb. The rank of the coal varies from sub-bituminous B to sub-bituminous A. The calorific value ranges from 4831 to 6060 kcal/kg, with an average value of 5644 kcal/kg. Annual production is about 460000 tonnes and coal resources are estimated to be about 50 million tonnes.

The Pir Ismail Ziarat coalfield is only 20 km^2 in area. It is situated 20 km south of Quetta and about 15 km north of Mach (29º 5’, 67º 51’). It consists of a north-south trending anticline with resistant Jurassic to Palaeocene limestone exposed in the core. The south-western part of the coalfield has been cut off by a large NW-SE trending thrust fault. There are two coal seams, the upper one is 0.6 – 0.7 m thick and the lower one is 0.4 – 0.45 m thick. The coal is high volatile bituminous C in rank and its moisture content ranges from 5.2 to 10%. Its heating value varies from 5353 to 5939 kcal/kg. Annual production is about 115,000 tonnes. Coal resources have been estimated at 11 million tonnes (Ahmed et al. 1986).

The Mach coalfield covers an area of about 45 km^2 around the town of Mach. Rocks of the Ghazij Group occur in a large synclinal structure, the greater part of which is covered by alluvial valley-fill. There are several coal seams ranging in thickness from 0.3 to 1.5 m though only 3 or 4 seams (average thickness 0.75 m) are workable. Rank ranges from sub-bituminous C to sub-bituminous B. Its heating value ranges from 5100 to 5730 kcal/kg (Ahmed et al 1986).Average annual coal production is about 125,000 tonnes. Resources are estimated at about 23 million tonnes (Ahmed et al. 1986).

The Kost-Harnai coalfield is the largest in Balochistan. It is located about 160 km SE of Quetta on the eastern flank of the Zhargun Molasse Basin. The Ghazi Group is exposed along the eastern margin of the basin and contains coal in its upper part. Coal mines are dotted along the ridge in a narrow belt about 40 km long and extend from NW of Khost (29º 12', 67º 05') to a few km SE of Harnai. The Khost-Harnai coal ranges in rank from lignite to bituminous B. The average rank is sub-bituminous C to A. Its heating value ranges from 4420 to 7000 kcal/kg. Average annual production is about 100,000 tonnes. Total coal resources are estimated at about 76 million tonnes.

The Duki coalfield is near the town of Duki (39º 09', 68º 34') in Loralai district, about 320 km east of Quetta. It comprises a moderately dipping, east-west trending 30 km and 5 to 10 km-wide asymmetric syncline. Rocks of the Ghazij Group crop out in the syncline although most of the central part is covered in alluvium. Coal is being mined on both limbs of the syncline. There are 17 coal seams of which 15 are worked. The Duki coal is high sub-bituminous B to C, though sub-bituminous A and even lignite are present (Khan et al. 1987). The heating value ranges from 4610 to 6380 kcal/kg. Average annual production of coal is around 25,000 tonnes. Coal resources are estimated at about 50 million tonnes.

3.2.2.3 Lower Sindh Coal Region

This coal region is in the southern part of the Kirthar stratigraphic province of the Indus Basin. A number of coal basins extend westwards from near Chachro (25º 40', 70º 15') in the Thar Desert through Badin (24º 40', 68º 50') to Lakhra-Sonda-Thatta area. Four coalfields have been explored: Lakhra, Sonda-Thatta, Meting and Thar. The coal occurs in the Middle Palaeocene Bara Formation and in the Sonhari Member of the Early Eocene Laki Formation. The Bara Formation contains two main coal-bearing horizons. The lower, Jherruck, coal zone is presently only known in the Sonda-Thatta coalfield. The Sonhari coal is restricted to the Meting coalfield.

The Lakhra coalfield is located about 20 to 25 km NW of Hyderabad and covers an area of approximately 300 km^2. Structurally it is a gently folded anticline (dip ± 5º) which has been dissected by several normal faults of 1.5 to 9 m displacement. Coal occurs in the Bara Formation 50 m to 150 below the surface. Nine of the coal seams are more persistent and three of these are of greater economic significance. The rank of the coal varies from lignite A to sub-bituminous C and its heating value ranges from 2570 to 4260 kcal/kg. Average annual production is about 1.5 – 2 million tonnes. Based on more than 244 drill holes, the coal resources of Lakhra are estimated to be about 1592 million tonnes.

The Sonda coalfield is located south of the Lakhra coalfields, between the towns of Thatta and Sonda, east of Karachi. It covers an area of more than 1400 km^2 and extends eastwards across the Indus up to Tando Mohammed Khan and beyond.

It comprises a very shallow anticline which has a dip of 2º or less. Coal occurs in thick lenses of siltstone and mudstone in the Bara Formation. More than 29 seams of varying thickness and persistence have been encountered. Coal occurs most persistently at three horizons, known as the Dadhuri, Sonda and Jherruck coal zones. In between these, four other zones with less persistent coal are referred to as the Upper Strays, Inayatabad, W and Lower Strays. The Sonda coal zone contains the thickest and most persistent coal bed, though in places it splits and becomes discontinuous or changes to carbonaceous shale. Near Jherruck the cumulative thickness of coal reaches 9 m and the Sonda coal attains a thickness of 6.2 m. The Sonda coal ranks from lignite A to sub-bituminous C. Its heating value ranges from 3600 to 5700 kcal/kg. Based on subsurface data from boreholes the coal resources of Sonda are estimated to be about 7300 million tonnes. The eastern extension of the Sonda coalfield has not yet been explored and more resources are likely to be present there.

The Meting coalfield covers an area of about 90 km^2 east of the railway line between Meting and Jhimpur (25º 01', 68º 01') railway stations. The coal is in the Sonhari Member of the Laki Formation of Eocene age, near the contact with the Upper Palaeocene Lakhra Formation. There is only one workable coal bed, which is commonly thin and lenticular and ranges in thickness from 0.3 to 1.0 m with an average thickness of 0.5 m. The Meting coal ranges from high volatile bituminous C to B. Average annual production of coal is about 40,000 tonnes. The total coal reserves based on a cut-off thickness of 0.6 m and a depth of 50 m are about 161 million tonnes.

The Thar coalfield is the largest in Pakistan and is located on the Indus Platform, in the Thar Desert in the SE corner of Pakistan. It covers an area of about 9000 km^2. It is covered by stabilised longitudinal sand dunes up to 250 m thick. It is found in a succession of Palaeocene-Eocene coal-bearing rocks 250-350 m thick, underlain by the Nagar Parkar granite. The coal-bearing sequence contains several coal seams of varying thickness, at depths ranging from 123 to 245 m. Some of the seams are more than 10 m thick, the largest being greater than 20 m in thickness. The measured coal resources of this field are about 78 billion tonnes. The coal is lignite B in rank with average heating value of 5333BTU, 1.57% sulphur, 8.83% ash and 48.57% moisture. The average dry ash-free heating value of Thar coal is 12322 BTU.

With the discovery of the Thar coalfield, Pakistan's coal reserves stood at 87.5 billion tonnes in 1997, and were the eleventh largest in the world.

Pakistan's coal beds have not yet been explored as potential carbon storage sites. Thar coalfield is Pakistan's largest, and, according to Sanjrani (2003) is situated over several brackish to saline water aquifers at depths of 50, 120, and 200m. The seams range from 0.2 to 22.81m in thickness. Thar has the thickest seams of all of Pakistan's coalfields, as none of the others exceed 6.2m (HDIP, 2005). In addition, other coalfields are all currently minable, and cannot, therefore, be considered as potential CO_2 storage sites.

3.2.3 Potential for CO_2 storage in saline water-bearing reservoir rocks in Pakistan

Only basins south of the frontal thrusts of the Himalayas and Karakoram were considered in the analysis below.

Both the Potwar Basin and the Lower Indus Basin have good potential for CO_2 storage in saline water-bearing reservoir rocks. However, insufficient geological data was available to quantify their saline aquifer CO2 storage capacity. The Balochistan Basin is considered to have limited potential at present. Brief descriptions of these basins are given below. Fuller descriptions are given in Appendix 3.

Potwar Basin

The Potwar Basin, sometimes known as the Kohat-Potwar or Upper Indus Basin, covers an area of about 40,000 km^2. It is bounded to the north and west by the Main Boundary Thrust – the southernmost of the major Himalayan thrusts. It is separated from the Lower Indus Basin to the south by the Salt Range and Sargodha High. It is bounded to the west by the Kurram Fault and to the east by the Jhelum Fault.

Reservoir rocks include Miocene alluvial sandstones, Paleogene shelf carbonates, Jurassic and Permian continental sandstones, and Cambrian alluvial and shoreface sandstones. Approximately 60% of the reservoirs are carbonates, in which oil and gas production may be largely from fractures. These reservoirs probably have little CO2 storage potential as they may not have the necessary storage volume in the structural or stratigraphic closures. The sandstone reservoirs have porosities ranging from 5 to 30%, averaging between 12 and 16%. Sandstone reservoir permeability ranges from 1 to >300 mD and averages 4 to 17 mD (Wandrey et al. 2004). The better sandstone oil and gas reservoirs therefore may have some potential for CO_2 storage. Seals include fault truncations and interbedded shales and the thick shales and clays of the Miocene and Pliocene Siwalik Group. In terms of aquifers, the Siwalik Group sandstone reservoirs may have significant storage potential, as should the aquifer portions of the better oil and gas field reservoir sandstones.

Lower Indus Basin

The Lower Indus Basin covers an area of about 400,000 km^2. It lies on the western margin of the Indian Plate and deepens steeply to the west. Its eastern margin is formed by the Punjab Shelf and Thar Platform, which are separated by the Jocobabad and Mari-Kandkhot Highs that lie partly in India. To the south, the basin extends offshore. The Thar Platform contains well developed Early to Middle Cretaceous sands that form the reservoirs of all the gas fields in this region. These sands would likely be the primary target for CO2 storage, at least initially, due to their proven seal at several locations.

Balochistan Basin

The Balochistan Basin covers an area of over 300,000 km^2. No commercial oil and gas discoveries have yet been made in it. It extends offshore to the south. The basin contains 5000 – 15000 m of flysch-type terrigenous slope and shelf sediments and turbidites. It is structurally complex, at least in the coastal area. There is no shortage of reservoir rocks, but overpressure has proved an operational problem, and this may reduce its potential for CO_2 storage.

3.3 MATCHING CO_2 SOURCES AND POTENTIAL GEOLOGICAL CO_2 STORAGE SITES IN PAKISTAN

Figure 3.3 shows the location of oil and gas fields, basins with good and fair aquifer storage potential and sources of CO_2 in Pakistan. Total emissions from large point sources in Pakistan are estimated to be 45 Mt CO_2 per annum. Total storage capacity in gas fields with capacity >10 Mt is estimated to be 1602 Mt CO_2. Therefore Pakistan's gas fields alone have the capacity to store current total emissions from large point sources for more than 35 years. Given that there is likely to be very significant aquifer CO_2 storage capacity in Pakistan's onshore and offshore sedimentary basins, it appears that Pakistan is well placed to deploy carbon dioxide capture and storage technology.

3.4 PRELIMINARY COST ESTIMATES FOR CCS IN PAKISTAN

For the sake of simplicity, we have divided the components of CCS into capture, transportation, and injection plus storage.

Table 3.8 summarises the cost ranges for CCS systems in the categories mentioned above.

Table 3.8 Cost ranges for CCS systems (power plants and industrial facilities)

CCS system components	Cost range	Remarks
Capture from a coal- or gas-fired power plant	15–75 USD/tCO_2 net captured	Net costs of captured CO_2, compared to the same plant without capture.
Capture from hydrogen and ammonia production or gas processing	5–55 USD/tCO_2 net captured	Applies to high-purity sources requiring simple drying and compression.
Capture from other industrial sources	25–115 USD/tCO_2 net captured	Range reflects use of a number of different technologies and fuels.
Transportation	1–8 USD/tCO_2 transported	Per 250 km pipeline or shipping for mass flow rates of 5 (high end) to 40 (low end) MtCO_2 yr-1.
Geological storage [a]	0.5–8 USD/tCO_2 net injected	Excluding potential revenues from EOR or ECBM.
Geological storage: monitoring and verification	0.1–0.3 USD/tCO_2 injected	This covers pre-injection, injection, and post-injection monitoring, and depends on the regulatory requirements.
Mineral carbonation	50–100 USD/tCO_2 net mineralized	Range for the best case studied. Includes additional energy use for carbonation.

Source: Intergovernmental Panel on Climate Change (IPCC), 2005

Estimating costs for these components of the CCS chain in Pakistan is an especially difficult task as neither CCS technology, nor any of its individual processes have yet been used in the country. The cost estimates have been made by comparison with the cost structures of:

- Oil company amine plants for CO_2 capture;
- Commercially available steel pipelines;
- Water injection systems in the oil industry;
- International CO_2 storage mechanisms.

No net-present value (NPV) calculations been made, as cash-inflow figures were not available.

3.4.1 Capture

Two different gas-processing plants in Pakistan (both owned by Orient Petroleum International Inc. [OPII]) were used to estimate the cost of CO_2 capture. The plant at Kausar field in Sindh has been used to show the capital costs involved, and the Khipro plant at Naimat Basal to show operations and maintenance (O&M) costs.

The Kausar field gas processing plant consists of a second-hand refurbished amine and TEG plant purchased from the US, that is capable of processing 100 million standard cubic feet per day (MMSCFD) of gas at any given time, and can purify 7 percent CO_2 contaminated natural gas. The hardware alone cost USD 5.2 million (Table 3.9). The final figure including other capital costs such as supervision and management, start-up spares, and construction comes to about USD 10.2 million. According to OPII engineers, a brand new amine plant can typically run into costs as high as USD 10 million, not counting construction costs. Engineers did however caution that the capital costs of gas processing plants cannot be benchmarked, as different levels of CO_2 contamination require different types of plants, and different design features (depending significantly on the chemical content of the raw gas). The O&M costs of this plant are not available.

Table 3.9 Capital costs of Kausar field gas processing plant

Description	Capital cost (Million USD)	Assumed annual O&M cost (Million USD)
Engineering outside Pakistan	0.26	0.41
Supervision/management	0.12	
Amine & TEG plant	5.21	
Materials, chemicals, start-up spares	1.74	
Freight	1.05	
Financial expenses	0.57	
Construction	1.12	
Surveying, local engineering, supervision	0.15	
3.4.1.1 TOTAL	10.20	

Source of capital costs: OPII, 2007

Table 3.10 below summarises the O&M costs of the Khipro gas processing plant for 2007. The costs have been divided into maintenance, services and rentals, and transport (not implying CO_2 transportation).

Table 3.10 O&M costs of Khipro gas processing plant

Description	O&M costs (USD)
Labour	Unavailable
Maintenance	861,000
Services and rentals	1,423,750
Transport	375,000
Total	2,659,750

Source: OPII, 2007

3.4.2 Transportation

The cost of transporting CO_2 depends on factors such as the distance between points of capture and injection, and terrain over which pipeline must travel. Therefore, local conditions must be considered when calculating such costs (IEA GHG, 2007b).

Sui is one of the largest natural gas fields in Pakistan, and has been supplying gas to the country for decades. Sui Southern Gas Pipelines Ltd. (SSGPL) and Sui Northern Gas Pipelines Ltd. (SNGPL) are the main distribution companies, and have an extensive network of pipelines running hundreds of kilometres. This network has been used to draw parallels and make infrastructure cost estimates for CO_2 transportation in the Pakistani context.

Natural gas is typically transported in a gaseous state at pressures ranging between 700 and 800 psi) in carbon steel pipes. There are several technical points to address when attempting to apply this formula to CO_2 transportation:

- CO_2 is a highly corrosive gas. This property is enhanced when water seepage into a CO_2 carrying pipe combines with the gas and forms a carbonic acid – hydrogen carbonate (H_2CO_3). If the seeping water has flowed through decaying vegetation (such as moss on pipes), it will absorb more CO_2 and become more acidic. Carbonic acids are well known as corroders of copper and galvanised plumping systems (APEC drinking water systems, undated). Therefore, the use of carbon steel pipes is not recommended as the danger of corrosion presents the added cost of repair and/or replacement. On the other hand, stainless steel piping, which is *much* more expensive, but resistant to corrosion, may be used.
- Being a gas, CO_2 is obviously quite compressible. Should a stoppage of flow occur for technical reasons at the source point or at the point of injection, the CO_2 can remain stored quite safely within the transport pipes for fairly long periods of time. The disadvantage of transporting gases in pipelines is the need for a constant pressure to ensure flow. CCS in Pakistan will likely require—potential storage sites have yet to be ascertained—very long distances across land to be covered before a suitable injection point can be reached. Pressure will thus be difficult to ensure, unless there are pumping devices—known in the natural gas industry as 'booster compressors'—available at regular intervals along the pipeline. According to Heddle et al (2003), such recompression is required every 150 Km. Engineers in Pakistan quoted a close figure of 100 Km. On average, a booster compressor used for this purpose can cost as much as USD 1 million a-piece.

Keeping the points above in mind, Table 3.11 below summarises costs of piping of 8, 12, 16, and 24-inch diameters of varying thickness, based on the rates of a well-known steel products company in Pakistan. The criteria supplied to the company were:

- The pipes should be able to withstand pressures of up to 150 bar or 2175.56 psi (Heddle *et al.*, 2003);
- They should be corrosion resistant as far as possible;
- They should be coated with anti-corrosion chemicals (outside coating);
- They should meet American Petroleum Institute (API) and Deutsches Institut für Normung e. V. (DIN) standards.

Table 3.11 CO_2 transport costs – on-shore pipelines

Pipeline diameter	Pipeline thickness	Capital costs (USD/Km)*	O&M costs (USD/Km)
8 inches	0.250	56,400	Unavailable
12 inches	0.312	95,550	
16 inches	0.406	140,533.33	
24 inches	0.562	265,066.67	

* Conversion to USD at rate: USD 1 = PKR 60

Note: Capital costs do not include sales tax

Source: Capital costs acquired from

Crescent Steel and Allied Products Ltd.

Another notable case study comes from the partnership formed between the National Fertilizer Company (NFC) and British Oxygen Company (BOC) Pakistan. The NFC's Pak-Arab Fertilizer plant in Multan has a fairly large urea production capacity. The major by-product is of course, CO_2, which is 96–98 percent pure. BOC Pakistan purchases this CO_2 and refines it further (up to 99.9 percent) at its CO_2 refining unit. The final product is pure liquefied CO_2. Unfortunately, we have been unable to procure capital and O&M costs for the refining and transportation processes.

3.4.3 Injection and storage

The injection of CO_2 into oilfields is a common technology utilized to enhance oil production. There are many other examples of this worldwide, for example, in Oman by Exxon Mobil. This technology has not yet been employed in Pakistan as such because all producing oil wells are quite young and possess pressures high enough to allow a natural upward flow. Water injection however, is being used to harness oil from tighter geological formations. Discussions with various engineers in Pakistan have lead to some basic cost estimates for such a set up. The most important component is a suitable pumping device. For this, a compressor of *at least* 1,500 horsepower at a cost of about USD 2 million will be required.

Discussions with production engineers at Orient Petroleum International Inc (OPII) revealed that the company has indeed done water injection, for both water disposal purposes, and oil enhancement. Pakistan's oilfields are all quite small, and have therefore never merited the added cost of CO_2 injection to enhance upward oil flow. Plus, the fields are mostly young ones, and usually possess sufficient natural pressure. OPII disposes off water (water vapour from oil wells) by injecting it into depleted oil wells that already possess a wellhead. The cost figures for an example of this are shown below in Table 3.12. The table shows the cost breakdown for a 5 Km transport line from the Naimat Basal oilfield to the depleted Naimat North field, where the injection takes place.

The final cost is just under USD 1 million. It must be noted however, that this example cannot be taken to reflect CO_2 injection costs with a particularly high degree of accuracy, because injected water need not be 'sealed', as leakage is not usually the problem it would be in the case of injected CO_2.

We were unable to procure costs estimates for projects where water injection was used for enhanced oil production.

Table 3.12 Naimat Basal produced water disposal at Naimat North

	Description	Cost (USD)	Cost (USD)
1	Water holding tank 500 BBLS (2 each)		60,000
2	Motor driven pumps (2 each)		140,000
3	Wellhead cartridge filter		40,000
4	Misc material (piping, fittings, valves, electrical and inst. Etc)		60,000
5	Chemical injection skid		40,000
6	Freight/transportation/duties		36,000
7	Civil, mechanical electrical and instrumentation construction works		100,000

8	Generator, area lighting for Naimat North well location			25,000
9	Facility engineering design services			25,000
10	Water disposal pipeline (4-inch diameter, 0.338 inch thickness) from Naimat Basal to Naimat North (5 Km)			414,000
	i	*Line pipe material cost including transportation to site*	135,000	
	ii	*Coating cost*	39,000	
	iii	*Fittings, valves, misc tie-ins material*	90,000	
	iv	*Cathodic protection system design/installation for pipeline*	13,000	
	v	*Pipeline construction*	100,000	
	vi	*Land leasing and crop compensation*	29,000	
	vii	*Survey, detailed engineering, EIA, permissions*	8,000	
11	OPII management			50,000
Total				**990,000**

Source: OPII, 2007

CO_2 storage has never been undertaken in Pakistan, not even for the purposes of EOR. It is therefore very difficult to estimate storage costs; at best, we can only rely on international estimates.

3.5 REFERENCES

APEC drinking water systems. Undated. http://www.freedrinkingwater.com/water-education2/75-carbon-dioxide.htm

Cook, Greg and Zakkour, Paul. Undated. *The new face of King Coal?* Environmental finance. http://www.environmental-finance.com/2005/0507jul/coal.htm

Federal Board of Statistics (FBS). 2006. *Pakistan Statistical Yearbook 2006.*

Heddle, G., Herzgog, H., and Klett, M. August 2003. *The economics of CO_2 storage.* Massachusetts Institute of Technology.

Hydrocarbon Development Institute of Pakistan (HDIP). 2005. Energy Yearbook of Pakistan 2005.

International Energy Agency (IEA) Greenhouse Gas (GHG). 2007. *CO_2 transmission cost calculator.*http://www.co2captureandstorage.info/co2costcalculator/co2transmission.htm

Intergovernmental Panel on Climate Change (IPCC). 2005. *IPCC Special Report on Carbon Dioxide Capture and Storage.* Prepared by Working Group III of the Intergovernmental Panel on Climate Change [Metz, B., O. Davidson, H. C. de Coninck, M. Loos, and L. A. Meyer (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 442 pp.

Kazmi, A.H. & Jan, M.Q. 1997. The Geology and Tectonics of Pakistan. Graphic, Karachi, 544 pp.

Ministry of Industries and Production (MoIP). 2007. http://www.pakistan.gov.pk/ministries/industriesandproduction-ministry/media/37items.pdf (Accessed 22 March 2007)

Orient Petroleum International Inc. (OPII). 2007. Personal communications. Islamabad, Pakistan.

4 Bangladesh

4.1 CO_2 SOURCES IN BANGLADESH

4.1.1 Introduction

Total CO_2 emissions from large point sources in Bangladesh recorded in the IEAGHG R&D programme database amount to some 17 Mt CO_2. The electrical power generation sector has the largest sectoral anthropogenic carbon dioxide emissions in Bangladesh (Table 4.1), which amount to 15.6 Mt CO_2. Most power generation is fuelled by natural gas (81%) and diesel, and there is a small contribution from hydro. In recent years a coal-based power station has been built close to the Barapukuria coal mine in NW Bangladesh and more are planned. Nevertheless, all power projects under construction are natural gas-based and located in the eastern part of the country.

The other major point sources are the two large cement works and the refinery at Chittagong.

There is a possibly significant seasonal emission in winter from small-scale (manual) brick manufacturing, which is disseminated throughout the country, although there is a significant concentration around Dhaka. Household gas burners may also contribute but there is little data available for either of these sources.

Table 4.1: The 20 largest point sources of CO_2 in Bangladesh.

Table 4.1 The 20 largest point sources of CO_2 in Bangladesh

No.	Sector	Installation name	Latitude	Longitude	Estimated annual CO_2 emissions (kilotonnes)	Status
1	Power	Ghorasal	23.93	90.63	4731	Open
2	Power	Barapukuria	25.53	88.97	2075	Open
3	Power	Ashuganj	24.03	91.02	1502	Open
4	Refinery	Eastern Refinery Ltd	22	92	983	Open
5	Power	Haripur Barge	24.88	88.72	980	Open
6	Power	Khulna	22.78	89.5	938	Open
7	Power	Chittagong	22	92	914	Open
8	Power	Haripur AES	24.88	88.72	653	Open
9	Power	Shajibazar	24.95	92.02	631	Open
10	Power	Shiddhirganj	23.68	90.52	631	Open
11	Power	Maghnaghat-1	23.47	90.82	490	Open
12	Power	Golapara	22.6	90.22	479	Open

13	Power	Maghnaghat-2	23.47	90.82	392	Open
14	Power	Dhaka	23.72	90.41	327	Open
15	Cement	Lafarge Surma Cement	24.05	91.08	262	Open
16	Power	Barisal Unocal	22.7	90.37	261	Open
17	Power	Haripur	24.88	88.72	218	Open
18	Power	Fenchuganj	24.88	91.87	182	Open
19	Power	Baghabari	28.29	89.63	181	Open
20	Cement	Chatak Cement	25.07	91.4	101	Open

4.1.2 Sectors

4.1.2.1 POWER

The state-owned Bangladesh Power Development Board initially owned all the power stations in Bangladesh. However, from 1998 private power companies (Independent Power Producers, IPP) started supplying power to the national grid. Additionally, the Rural Electrification Board owns one power station which also provides power to the national grid. Most of the power stations are gas-based steam turbine generators and high speed diesel-based gas turbines. Later combined cycle gas turbines were established. In 2005-06 Bangladesh's first coal-based power plant was put into operation, at Barapukuria in Dinajpur, based on the coal from Barapukuria Coal Mine.

The present installed generation capacity is 5275 MW. However, there is always a power shortage in the country. Indigenous gas-based generation is 4301MW (81.54%), hydro capacity is 230MW (4.36%), liquid fuel-based capacity is 494MW (9.36%), and coal-based generation is 250MW (4.74%), (Source BPDB).

Annual CO_2 emissions from gas-based plant in 2006 are estimated at 15.071 Mt. A few units always remain out of the grid due to maintenance.

The national power sector plan, drawn up in 1995, indicates that, after installation of new gas-based power plant, in 2020 the power generation capacity of gas-based plants is expected to stand at 6150 MW and the estimated CO_2 emission will be 21.55 Mt.

In Bangladesh, power plants typically comprise several 'units', in many cases burning different fossil fuels. Where a unit generates power utilizing dual-fuel combustion, the power produced in KWh by each type of fuel have been separated, and the relevant emissions factor used. The highest capacity single gas-fired units are 450 MW and the smallest is 20 MW. Power generation using diesel is mainly used in standby generators in industries and commercial buildings. The estimated installed capacity is reported to be around 1500 MW. It is difficult to calculate emissions as these units do not run on a continuous basis and operational data is not readily available. It must however, be emphasised that due to the acute power shortage in the country, local generation will be increased steadily and in the future will be a significant emitter that will have to be taken in consideration.

The general convention for calculating CO_2 emissions from the burning of fossil fuels for the production of electricity involves multiplying the appropriate emission factor by the production of electricity of each power plant in KWh. The de-rated power plants of capacity between 800-900 MW contribute significantly more CO_2 than the recently built Combined Cycle Plants.

4.1.2.2 FERTILIZER

There are 10 fertilizer plants in Bangladesh of which seven produce Urea, one TSP and two DAP. The CO_2 generation from the process is very small and therefore their contribution to national emissions is negligible.

Each of the plants has its own in-house power generation unit but these are generally small, ranging between 16-24 MW. They are used primarily to run critical units. The contribution to national CO_2 emissions from these units is small. A very few SSP type fertilizer plants are in operation but these do not have large in-house power generation facilities.

In 2004, natural gas consumption in the fertilizer sector was 12821 million m^3 (source BCIC).

4.1.2.3 CEMENT

With over 13 plants scattered over the country, the Bangladesh cement industry produced 4.6 million tonnes of Portland cement in 2006.

Calcination takes place in two plants only. Both of them are located in the Sylhet area (NE Bangladesh). The Chattak Cement Co. Limited has capacity of 150,000 T/yr and Surma Lafarge Cement Limited has 600,000 T/yr.

There are 11 other units which import clinker from abroad and grind it in Bangladesh. The non-clinker-producing plants' contribution to national CO_2 emissions is insignificant.

CO_2 emissions from the cement sector are estimated to be between 438-648 Ktn/Yr.

4.1.2.4 REFINERY

Bangladesh has one oil refinery consisting of two relatively small capacity units. The existing refinery has about 1.5 million tonnes refining capacity. Its existing units produce 665kt and 318kt CO_2 per year respectively. An additional refinery may be established on the same premises by 2010. When the planned bigger capacity unit is installed CO_2 generation will be more than doubled, because the present capacity meets only 33% of the country's requirements and the new unit is planned to meet the country's full oil demand.

4.1.2.5 HEAVY INDUSTRY

Apart from the sectors described above, there is very little heavy industry in Bangladesh. The main industrial growth is in the ready-made garments and textile sector. The small iron and steel industry consumes some gas but its contribution to national CO_2 emissions is thought to be insignificant.

4.1.2.6 BRICK FIELDS:

In Bangladesh bricks are produced using coal or firewood as fuel. Brick manufacture is seasonal, taking place in the winter, and disseminated through the whole country, although there is a concentration of kilns around Dhaka. There is no data available on carbon dioxide emissions from these kilns.

4.1.2.7 CONCLUSIONS

Prior to the current study, very little information was available on industrial CO_2 emissions in Bangladesh. The current study indicates that there are clusters of power plants in the Ashuganj and Ghorashal belt (Lat 24N, Long 90.5E), close to the capital Dhaka, in the central part of

Bangladesh. There is a probability that, within the next ten years, another cluster may develop in the north of Bangladesh where coal is available, which will be used to generate power.

4.2 POTENTIAL GEOLOGICAL CO_2 STORAGE SITES IN BANGLADESH

4.2.1 Introduction

The potential geological CO_2 storage sites of Bangladesh considered in detail in this report are divided into the following categories:

- saline water-bearing reservoir rocks,
- oil and gas fields
- coal seams

The are no outcropping basalt rock formations in Bangladesh

4.2.2 Oil and gas fields

There are no oil fields in Bangladesh although there is minor production of condensate or light oil from some of the gas fields. The location of gas fields in Bangladesh is shown in Figure 4.1.

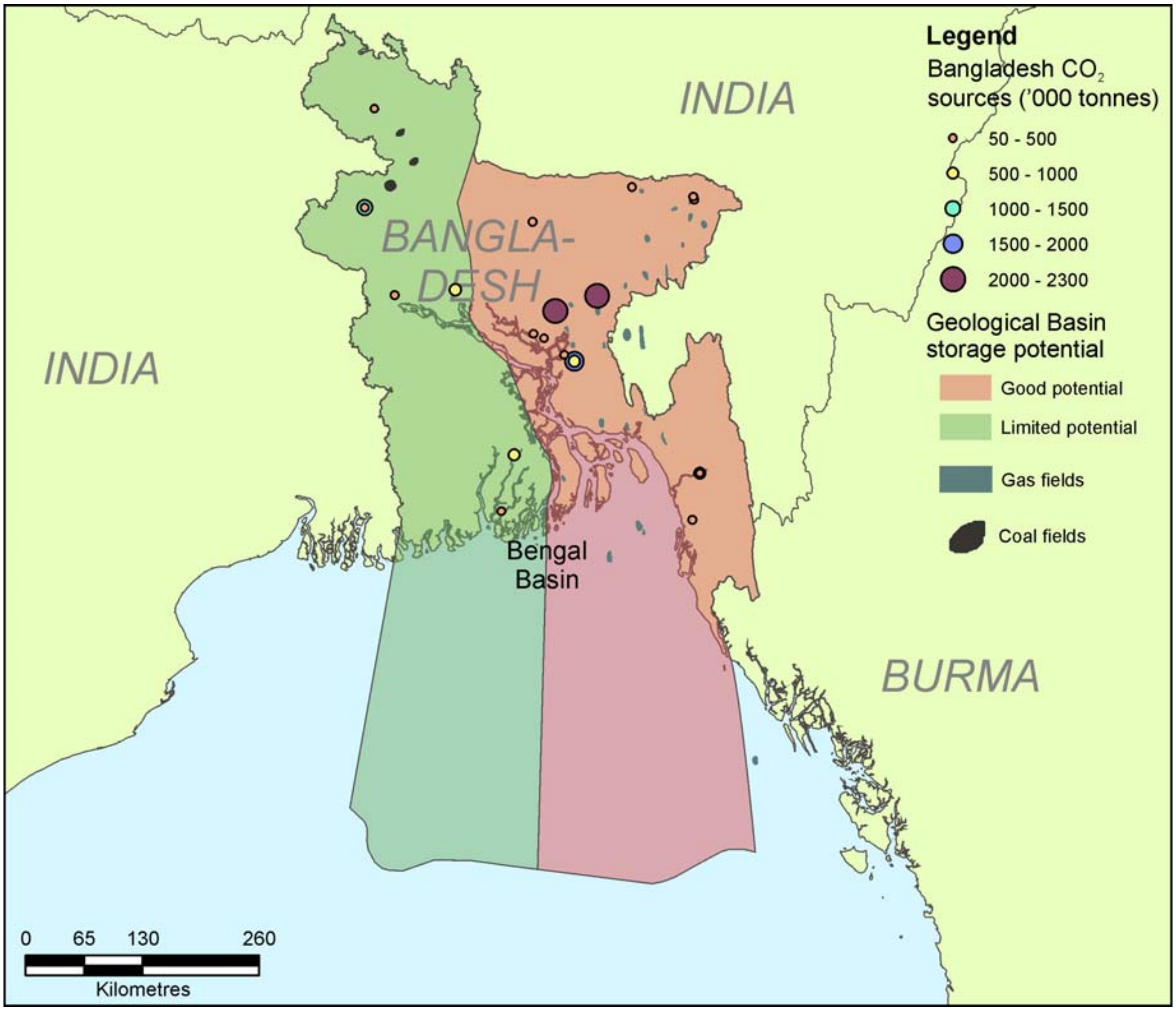


Figure 4.1 Location of CO_2 point sources and potential geological storage sites in Bangladesh

Table 4.2 shows the estimated CO_2 storage capacity of gas fields in Bangladesh.

Table 4.2 Estimated CO_2 storage capacity of gas fields in Bangladesh

Field name	Status	Discovery	Estimated URR bcm	Estimated GEF	Estimated CO_2 density reservoir conditions tonnes m^{-3}	Estimated CO_2 storage capacity 10^6 tonnes
Bakhrabad	In production	1969	30	200	0.6	58
Beanibazar	In production	1981	5	200	0.6	9
Habiganj	In production	1963	109	200	0.6	213
Jalalabad	In production	1989	24	200	0.6	46
Kailashtila	In production	1962	54	200	0.6	105
Meghna	In production	1990	3	200	0.6	7
Narshingdi	In production	1990	6	200	0.6	12
Rashidpur	In production	1960	40	200	0.6	77
Sangu	In production	1996	24	200	0.6	47
Saldanadi	In production	1996	3	200	0.6	6
Sylhet	In production	1955	14	200	0.6	26
Titas	In production	1962	145	200	0.6	283
Feni	In production	1981	4	200	0.6	7
Begumganj	Not in production	1977	1	200	0.6	2
Bibiyana	Not in production	1998	68	200	0.6	133
Fenchuganj	Not in production	1988	8	200	0.6	16
Kutubdia	Not in production	1977	1	200	0.6	3
Semutang	Not in production	1969	4	200	0.6	8
Shahbazpur	Not in production	1995	13	200	0.6	26
Maulavibazar	Not in production	1997	10	200	0.6	20
Chattak	Production suspended	1959	13	200	0.6	26
Kamta	Production suspended	1981	1	200	0.6	3
Total			**581**			**1133**

Fourteen of the gas fields have estimated CO_2 storage capacities >10 Mt. Two have estimated CO_2 storage capacities >200 Mt. Given that Bangladesh's emissions from large point sources are approximately 11 Mt year^{-1}, the storage capacity in gas fields alone appears adequate for some time to come.

4.2.3 Coal fields

Bangladesh has three concealed coalfields: Jamalganj, Khalaspir and Barapukuria (Holloway & Baily 1995). All are in the NW of the country, west of the Jamuna River (Figure 4.1). The only field that has been exploited to date is Barapukuria, which is being mined at present. Additionally, coal has been discovered in a borehole at Dighipara, at a depth of about 2398 m. Coal is also present at depth in the Kutchma X-1 and Singra-1 oil exploration wells (at and below 2714 m and below 3080 m respectively). There is also some near-surface coal in the extreme NW of the country, near Phulbari in Dinajpur district. This is likely to be too shallow to be able to adsorb significant amounts of CO_2, even if it was not required as an energy resource.

The Jamalganj coalfield was discovered in the early 1960s and is known from 11 boreholes. It is thought to occupy an area of about 37 km^2 (Rahman & Zaher 1980). The coal is at depths of approximately 640-1100 m and occurs in the Raniganj Coal Formation, of Permian age. Up to 7 seams are present and there is significant variation in seam thickness: seam 3 varies between 4.63 and 27.32 m thick. Rank is high volatile bituminous B. Ash content is about 22-25%. Reserves are estimated to be between 1,053 million tonnes and 1563 million tonnes (Rahman & Zaher 1980). Key factors relevant to its CO_2 storage potential, such as coal permeability and its gas storage potential, are unknown. The core from the Jamalganj coalfield was stored in Quetta (at the time in West Pakistan) prior to Bangladesh's independence and has now been lost. No isotherms are available.

Assuming the Jamalganj coalfield could be used for CO_2 storage, and the coal seams were sufficiently permeable, and an average of 0.02 tonnes CO_2 (Appendix 1) could be stored per tonne of coal, its CO_2 storage capacity is estimated to be between approximately 20 and 31 Mt CO_2.

The Khalaspir coalfield was discovered in 1989. The coal-bearing area is approximately 12.26 km^2 (Nazrul Islam et al. 1991). Within this area, Gondwana coals are present at depths of 257-481 m below surface. Up to 8 coal zones, consisting of coals interbedded with carbonaceous mudstone and sandstone, are present. Up to 6 seams are present in each zone, seams range in thickness from 0.6 to 15 m (Landis et al. 1990). Mean ash content is 21.8%. Rank is high volatile bituminous A to low volatile bituminous. Estimated proven reserves are 143 million tonnes, estimated proven plus probable reserves are 685 million tonnes.

Assuming the Khalaspir coalfield could be used for CO_2 storage, and the coal seams were sufficiently permeable, and an average of X tonnes CO_2 could be stored per tonne of coal, its CO_2 storage capacity is estimated to be between 3 and 14 million tonnes.

The Barapukuria coalfield is being mined. Even if the thinner seams are not mined, they will effectively be exposed to surface pressure conditions and will not have the potential to adsorb significant amounts of CO_2. The Barapukuria coalfield therefore has no CO_2 storage potential.

Gas content analysis of the Barapukuria coal showed that it contained negligible amounts of methane (Norman 1992).

The Dighipara coal discovery is only known from one borehole. Its top is at a depth of 328 m. Seam 1, the shallowest seam is 27 m thick in the Dighipara borehole. A second seam, unbottomed but at least 12 m thick, occurs from 348 – 360 m. Gas content analysis shows that it contains negligible amounts of methane. The coalfield is thought likely to be too small and too shallow to store significant amounts of CO_2.

4.2.4 Saline water-bearing sedimentary rocks (saline aquifers)

The greater part of Bangladesh lies in the eastern part of the Bengal Basin (Figure 4.1). In the north of the country there is a buried basement ridge known as the Rangpur Saddle that runs between the Shillong Plateau and The Rajmahal traps (both in India). The Bengal basin becomes progressively more folded to the east and eventually merges into the Assam-Arakan fold belt, which occurs in the Chittagong Hill tracts of eastern Bangladesh. The CO_2 storage potential of the Bengal Basin and Assam-Arakan Fold Belt is described in Appendix 3. The eastern, folded half of the Bengal basin in eastern Bangladesh has excellent CO_2 storage potential in the many anticlines that are found there. There is also likely to be large potential in the Chittagong Hill Tracts, although this region is remote from many large point sources and may suffer from overpessure, at least locally. The western half of Bangladesh, west of the Jamuna River suffers from a lack of structural closures suitable for containing geologically stored CO_2, and so may have less storage potential.

4.3 MATCHING CO_2 SOURCES AND POTENTIAL CO_2 STORAGE SITES IN BANGLADESH

The majority of the major CO_2 sources and all the gas fields in Bangladesh occur east of the Jamuna River (Figure 4.1). Moreover, all the likely saline aquifer CO_2 storage capacity is in this area too. Thus there is an excellent match between sources and potential storage sites in Bangladesh. Given that the estimated gas field CO_2 storage capacity alone is of the order of 100 times larger than the current annual emissions of CO_2 from large point sources, in can be stated with certainty that Bangladesh is well placed to take advantage of carbon dioxide capture and storage technology in the future.

4.4 REFERENCES

Holloway, S. & Baily, H E. 1995. Coalbed methane pre-feasibility study - northwest Bangladesh. *BGS Technical Report WC/95/59R. Overseas Geology Series,* 52pp.

Rahman, R.R. & Zaher, M.A. 1980. Jamalganj Coal – its quantity, quality and minability. *Petroleum and Mineral Resources of Bangladesh, Proceedings of the Seminar and Exhibition, 8-12 October 1980.* Peoples Republic of Bangladesh, 41-53.

Nazrul Islam, M., Nehal Uddin, M., Resan, S.A., Sultan-Ul-Islam, M. & Wazed Ali, M. 1991. Geology of the Khalspir Coal Basin, Pirganj, Rangpur, Bangladesh. *Records of the Geological Survey of Bangladesh,* Volume 6, Part 5.

Norman, P.S. 1992. Evaluation of the Barapukuria coal deposit NW Bangladesh. *In:* Annels, A.E. (ed.) Case Histories and Methods in Mineral Resource evaluation. *Geological Society Special Publication* 63, 107-120.

5 Sri Lanka

5.1 CO_2 SOURCES IN SRI LANKA

The IEAGHG R&D programme CO_2 sources database indicates that three categories of major CO2 sources are present in Sri Lanka.

5.1.1 Power plants

Electricity demand in Sri Lanka is increasing by about 10% annually, see http://www.fabm.gov.lk/downloads/Norochcholai.pdf. Sri Lanka produces 37% of its electricity from hydropower and the remainder from fossil fuel-fired power plants. There are 6 major fossil fuel-fired power plants in the country, all of which are oil fired. These 6 plants have annual total estimated emissions of 1.7 Mt CO_2.

Because of the high cost of, and demand for, electricity, a 900 MW coal-fired power plant is under construction at Norochcholai in northwest Sri Lanka, the first stage of which is set to add an initial 300 MW of power to the national grid by the end of 2010. The plant will use imported coal.

Further coal-fired power plants are planned. A press release from the Indian High Commission in Colombo on 29 December 2006, stated that a Memorandum of Agreement was signed between NTPC Ltd., (a Government of India Undertaking), Ceylon Electricity Board and the Government of Sri Lanka for setting up of a 500 MW coal based thermal power plant at Trincomalee. The power plant is expected to commence operations from 2011. The process of site selection in Trincomalee commenced with the signing of the Agreement.

5.1.2 Cement plants

The IEAGHG R&D programme CO_2 sources database indicates that there are two major cement plants in Sri Lanka, which were emitting an estimated annual total of 611 Kt CO_2. The plant at Puttalam on the NW coast is the larger, with emissions estimated at 419 Kt CO_2 per year. The plant at Kankesanturai, near Jaffna, was estimated to have annual emissions of 192 Kt CO_2 but is currently closed.

5.1.3 Refineries

The only other major CO_2 source in the database is the oil refinery at Sapugaskanda, near Colombo, which emits an estimated 458 Kt CO_2 per annum.

5.1.4 Conclusions

The total annual emissions of CO_2 from large point sources in Sri Lanka are very small, and estimated to be approximately 2.6 Mt. These will be increased by the operation of new coal-fired power plant, but national emissions will still be very small in global terms.

All major point sources of CO_2 in Sri Lanka that are recorded in the IEAGHG R&D Programme CO_2 sources database are shown in Figure 5.1.

5.2 POTENTIAL GEOLOGICAL CO_2 STORAGE SITES IN SRI LANKA

Geologically, most of onshore Sri Lanka is made up of Precambrian crystalline rocks with no CO_2 storage potential. The only significant development of sedimentary rocks onshore is along the NW coast, where Miocene limestones overlie the Precambrian basement.

There are no significant coal deposits known in Sri Lanka. No oil fields or gas fields have been discovered to date, but there is oil and gas potential in the Sri Lankan side of the Cauvery Basin, offshore to the north of the island, in Palk Bay and the Gulf of Mannar. According to press reports from 2006, the Minister of Energy and Power stated that potential reserves of oil and gas in Sri Lanka's territorial waters within the Cauvery Basin in the Palk Straits are estimated to be equal to between 10 and 20 million barrels of oil, while the Mannar basin may hold oil and gas reserves equivalent to 100 million barrels of oil. There may be some saline aquifer CO_2 storage capacity in this area as well, but it cannot be quantified at present.

5.3 MATCHING CO_2 SOURCES AND POTENTIAL GEOLOGICAL CO_2 STORAGE SITES IN SRI LANKA

The major sources of CO_2 in Sri Lanka are shown in Figure 5.1. The only potential geological storage sites are offshore, in the Sri Lankan side of the Cauvery Basin, to the N and W of the island. The storage capacity in this area cannot be quantified at present, so no estimate of the national potential relative to national emission from large point sources can be made. However, the new coal-fired power plant under construction at Norochcholai is relatively well placed with respect to the inferred CO_2 storage potential in the Cauvery Basin.

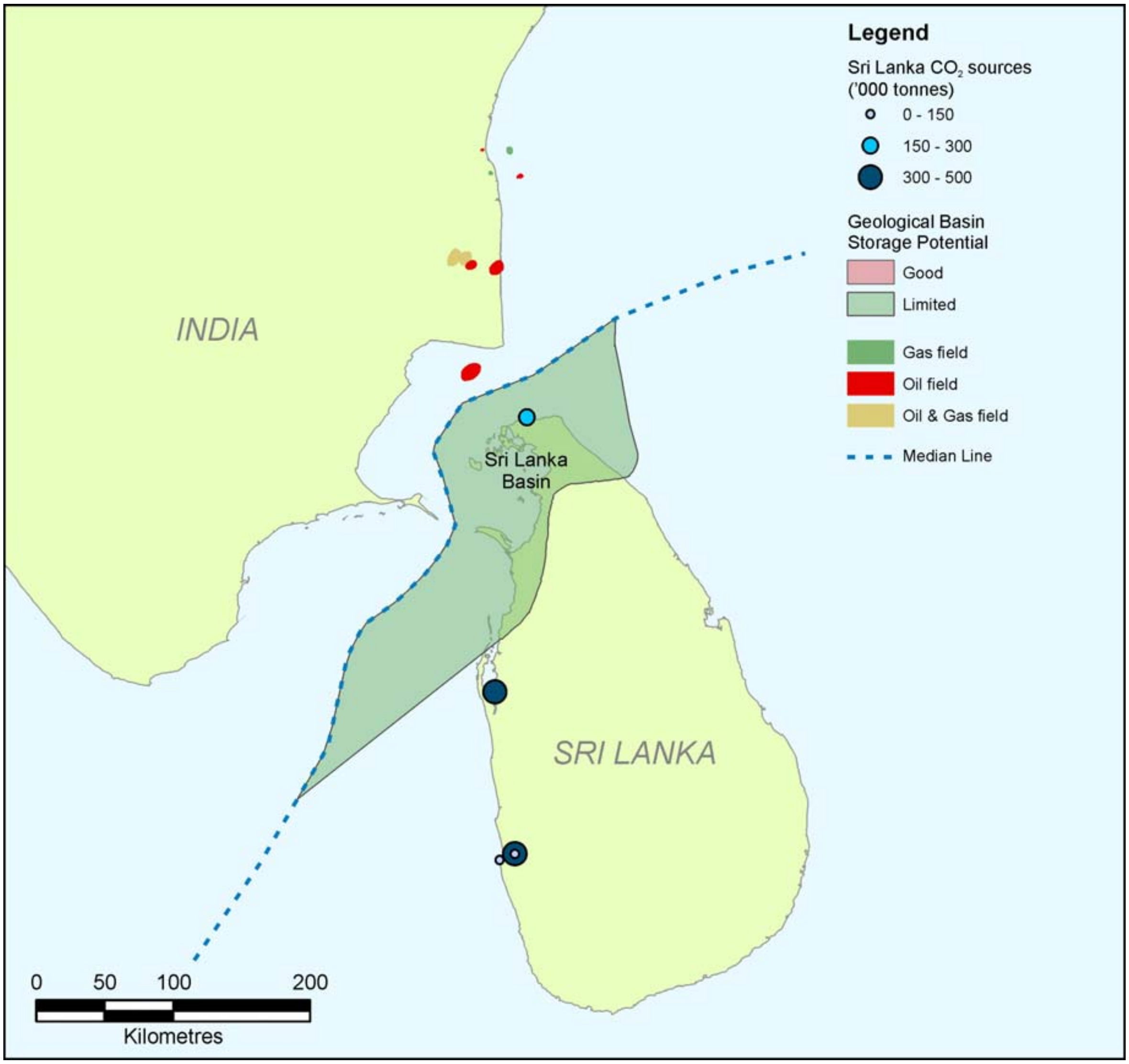


Figure 5.1 Location of CO_2 sources in Sri Lanka and the oil and gas fields of the Cauvery Basin

5.4 REFERENCES

Herath, J.W. 1985. *Economic Geology of Sri Lanka*. Natural Resources, Energy and Science Authority of Sri Lanka, Colombo.

Cooray, P.G. 1984. *An Introduction to the Geology of Sri Lanka*. National Museums of Sri Lanka, Colombo.

Appendix 1 Methodology for estimating geological CO_2 storage capacity

The assessments of geological CO_2 storage capacities in this report conform as far as is possible to the methodology recommended by the CSLF (Bradshaw et al. 2007, Bachu et al. 2007).

Geological CO_2 storage capacity can be considered in the same terms as any other resource: parts of it are well known - there is relative certainty about the existence and magnitude of this fraction. On the other hand, other (larger) parts of the resource are much more speculative and poorly quantified. It can be helpful to consider the CO_2 storage potential of India, Pakistan, Bangladesh and Sri Lanka as a resource pyramid, which has a very wide base consisting of speculative potential, and an apex consisting of well-quantified and relatively certain capacity (Bradshaw et al. 2007). The *theoretical* CO_2 storage capacity is represented by the entire pyramid and comprises the entire resource. A large part of it, visible at the base of the resource pyramid consists of speculative, poor quality and poorly quantified or unquantified potential. The *effective* storage capacity is capacity which meets a range of basic geological and engineering criteria and which can be quantified with a fair degree of confidence. It comprises all the capacity excluding the speculative, poor quality or poorly quantified potential. The *practical* capacity is a subset of the effective storage capacity that consists of potential storage sites that meet additional criteria and can be considered in terms of the annual CO_2 storage rates that they might accommodate. Finally, at the apex of the pyramid, is *matched* storage capacity; a subset of the practical capacity that is obtained by detailed matching of large stationary CO_2 sources with geological storage sites that are adequate in terms of capacity, injectivity and supply rate.

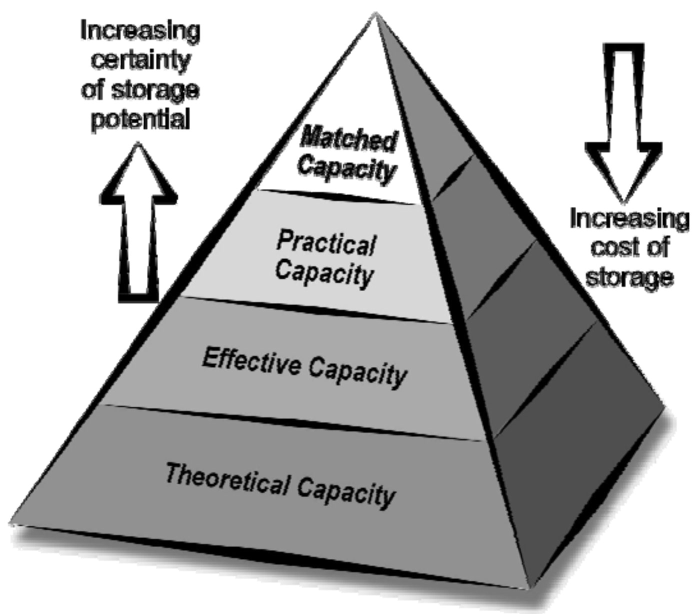


Figure A1.1. CO_2 storage capacity resource pyramid (after Bachu et al. 2007)

Bachu et al. (2007) affirm that country-scale assessments of CO_2 storage capacity should be performed to determine whether there is sufficient storage capacity in a country, what type or types of storage capacity are available and what challenges (or risks) may exist, without necessarily quantifying that country's potential. This is because the recommended CSLF methodology for quantifying storage capacity relies on the availability of a large geological dataset for each potential storage medium (i.e. oil and gad gas fields, coal fields and saline aquifers). For India, Pakistan and Bangladesh, much of the necessary data is not in the public domain and so a fully quantitative estimate of their CO_2 storage capacities could not be made. However, a qualitative comparison of the storage capacity with that of the European sector is given in Appendix 4. This employs the same methodology as used in the IEAGHG European sector study (Wildenborg et al. 2006).

Many approximations and assumptions have had to be made in the analysis. These are described in more detail in the text of the report. Therefore the estimates given in the report should be revised when more accurate data becomes available. The estimates presented represent the views of the authors and not necessarily those of the IEAGHG R&D programme, DEFRA or the countries concerned.

OIL AND GAS FIELDS

Assumptions

Following Bachu et al. (2007) the underlying assumption made in the estimates of the CO_2 storage capacity of oil and gas fields is that the volume previously occupied by the produced hydrocarbons is available for CO_2 storage. This assumption is generally valid for pressure-depleted reservoirs that are not in hydrodynamic contact with an aquifer, or that are not flooded during secondary and tertiary oil recovery. In reservoirs that are in hydrodynamic contact with an underlying aquifer, or are purposefully water-flooded during secondary production, formation water or injected water invades the reservoir as the pressure declines because of production, leading to a decrease in the pore space available for CO_2 storage. CO_2 injection can partially reverse any water influx, thus making more pore space available for CO_2. However, not all the previously hydrocarbon-saturated pore space will become available for CO_2 because some of the invading water will be trapped in the pore space due to capillarity, viscous fingering and gravity effects (Stevens et al., 2001).

Another important assumption is that CO_2 will be injected into depleted oil and gas reservoirs until the reservoir pressure is brought back to the initial (virgin) reservoir pressure. In some cases reservoir depletion could damage the integrity of the reservoir and/or caprock, in which case it might not be possible to inject until the initial reservoir pressure is reached and the capacity would be lower. In other cases the pressure could be raised beyond the original reservoir pressure as long as it remains safely below the lesser of the capillary entry pressure and the threshold rock-fracturing pressure of the seal (caprock), in which case the CO_2 storage capacity would be higher due to CO_2 compression. However, raising the storage pressure to or beyond the original reservoir pressure requires a case-by-case reservoir analysis that is not practical for basin-scale evaluations.

Finally, in many cases the structure that hosts a hydrocarbon reservoir is not filled with oil and/or gas to the spill point. In such cases, the additional pore space down to the spill point might also be used for CO_2 storage, but, to achieve this, the pressure would have to be increased beyond the original reservoir pressure, as discussed previously. In the time available for this study, it was not possible to determine which of the oil and gas fields were filled to spill point, so it was assumed that they were all full to spill point before production started.

Storage capacity calculations

There is no published information at all about many of the oil and gas fields in India. The CO_2 storage capacity of these fields could not be estimated individually. State-by-state reserves figures are available in India but the reserves quoted are remaining reserves rather than remaining plus recovered reserves.

For many other fields only the ultimately recoverable reserves (URR) of oil and gas are publicly available. In order to estimate the pore space occupied by the URR, several assumptions had to be made. These are listed below:

- Unless field-specific information is available, it is assumed that all gas produced from fields with oil production is dissolved gas, the reservoir volume of which can be accounted for by applying a formation volume factor (FVF). This will likely result in an underestimate of CO_2 storage capacity because some of the fields likely have gas caps, and this pore space will not be accounted for in the calculations.
- The formation volume factor applied to all oil fields is 1.2 unless there is field-specific information available.
- Where the initial reservoir temperature and pressure are not known, the density of CO_2 under reservoir conditions is assumed to be 600 kg m^{-3}.

Using these assumptions, the pore space occupied by the ultimately recoverable reserves in an oil field is estimated as follows:

$M_{CO2} = (V_{OIL}\ (stp).B_o)\ .\ \rho CO_2$ (Equation 1)

Where:

M_{CO2} = CO_2 storage capacity

stp = standard temperature and pressure

V_{OIL} (stp) = volume of ultimately recoverable oil at stp

B_o = oil formation volume factor (the ratio between a volume of oil and the dissolved gas that it contains at reservoir temperature and pressure and the volume of the oil alone at stp)

ρCO_2 = density of CO_2 at reservoir conditions (kg m^{-3})

The pore space occupied by the ultimately recoverable reserves in a gas field is calculated as follows:

$M_{CO2} = (V_{GAS}\ (stp) / Bg)\ .\ \rho CO_2$ (Equation 2)

Where:

M_{CO2} = CO_2 storage capacity (10^6 tonnes)

Stp = standard temperature and pressure

V_{GAS} (stp) = volume of ultimately recoverable gas at stp (10^9 m^3)

Bg = gas expansion factor (from reservoir conditions to stp)

ρCO_2 = density of CO_2 at reservoir conditions (kg m^{-3})

The pore space occupied by the URR was then discounted by 35% to allow for water invasion into the reservoir and/or water injection into oilfields for secondary recovery.

COAL FIELDS

The methodology used to estimate the CO_2 storage capacity of India was:

1. Estimate the mass of coal that might be available for CO_2 storage in each coal field.
2. Estimate the average mass of CO_2 that might be stored per tonne of coal, using an absorption coefficient and a saturation coefficient.
3. Multiply the above to derive the potential CO_2 storage capacity.

All the important factors in the above method involve a degree of judgement. The estimate the mass of coal that might be available for CO_2 storage in each coal field was based on expert judgement by one of the authors. The estimate of the average mass of CO_2 that might be stored per tonne of coal is based on an arbitrary assumption that the average sorption capacity if in situ Indian coal available for CO_2 storage is 16.6 standard m^3 CO_2/tonne raw untreated coal and 60% saturation of the available sorption sites can be achieved (the latter following the rule of thumb proposed by Bromhal et al. 2003). On this basis approximately 10 standard m^3 CO_2/tonne coal (approximately 0.02 tonnes CO_2/tonne coal) can be stored. It was assumed that all coal available for CO_2 storage is of sufficient permeability. At greater depths the sorption capacity may be greater but the achievable saturation is likely to be lower because of the reduced permeability.

No account was taken of the ECBM potential of Indian coal as this is not known for all coalfields.

REFERENCES

Bradshaw. J., Bachu, S., Bonijoly, D., Burruss, R., Holloway, S., Christensen, N-P. Mathiasen, O-M.2007. CO_2 storage capacity estimation: Issues and development of standards. *International Journal of Greenhouse Gas Control,* **1**(1), 62-68.

Bachu, S., Bonijoly, D., Bradshaw, J., Burruss, R., Holloway, S., Christensen, N-P. & Mathiassen, O-M. 2007. CO_2 storage capacity estimation: Methodology and gaps. *International Journal of Greenhouse Gas Control,* **1**(4), 430-443.

Bromhal, G.S., Sams, N.W., Jikich, S., Ertekin, T. & Smith, D.H. 2005. Simulation of CO_2 sequestration in coal beds: The effects of sorption isotherms. *Chemical Geology* **217**(3-4): 201-211.

Stevens, S.H., Kuuskraa, V.A. & Gale, J. 2001. Sequestration of CO_2 in Depleted oil and Gas Fields: Global Capacity, Costs and Barriers. *Proceedings of 5th International Conference on Greenhouse Gas Control Technologies,* (ed. D. Williams B. Durie, P. McMullan, C. Paulson & A.Smith), Collingwood, Australia: CSIRO, pp. 278-283.

Wildenborg, A., Gale, J., Hendriks, C., Holloway, S., Brandsma, R., Kreft, E. & Lokhorst, A. 2006. Cost Curves for CO_2 storage, European Sector. *In*: Rubin, E.S., Keith, D.W. & Gilboy, C.F. (eds.), *Proceedings of 7th International Conference on Greenhouse Gas Control Technologies*. Volume 1: Peer-Reviewed Papers and Plenary Presentations, Elsevier, p. 603-610.

Appendix 2 Description of the major coalfields of India

Space precludes a detailed field-by-field description of each coalfield, for which the reader is referred to the Coal Atlas of India (1993). However a summary of each of the major coalfields, abstracted from the Coal Atlas of India, is given below and their locations are shown in Figure A2.1.

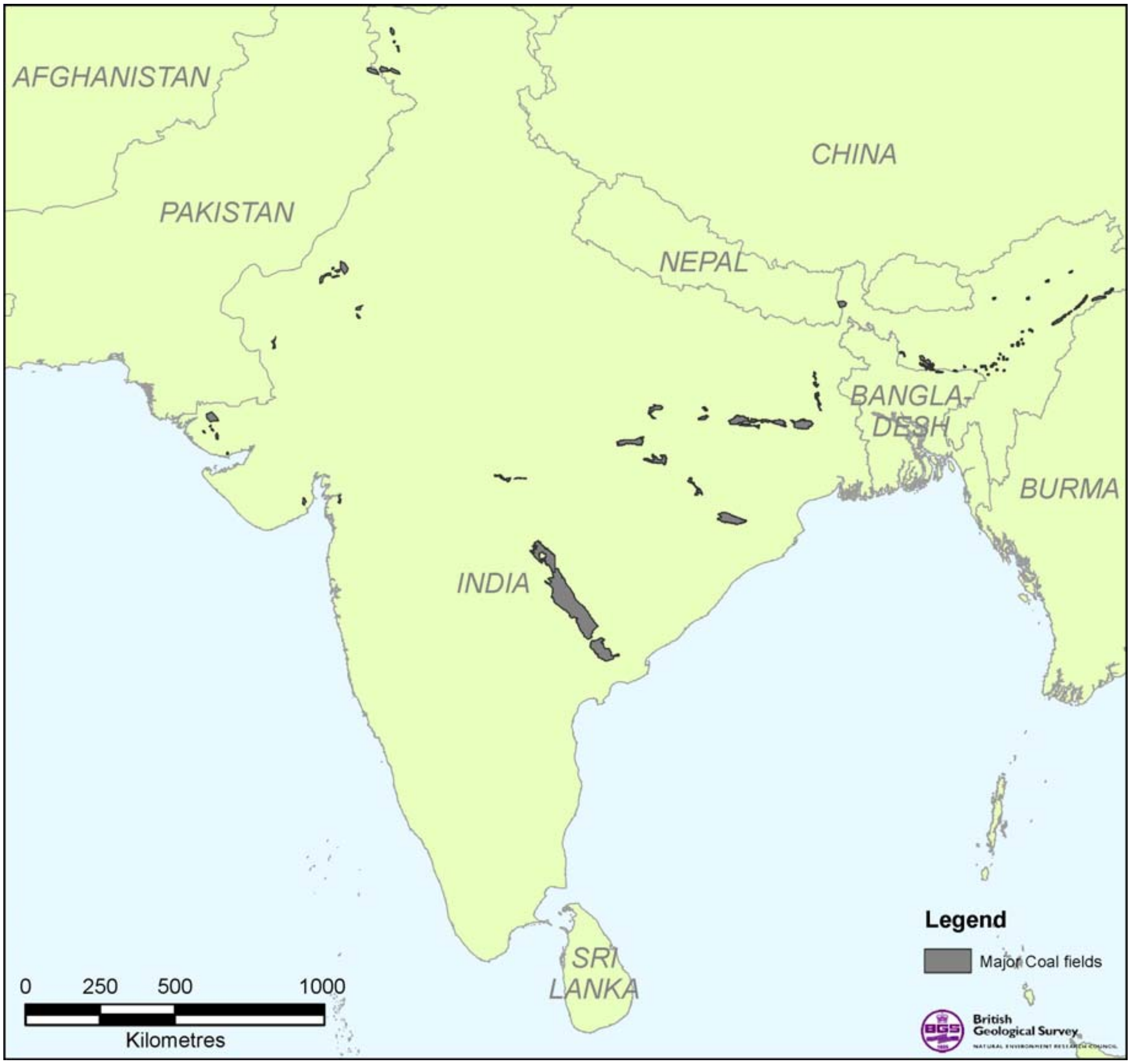


Figure A2. 1 Location of the major coalfields of India

THE RANIGANJ COALFIELD

This is the easternmost field in the Damodar valley (Figure A2.1). It lies mainly in West Bengal but also partly in Bihar. It is a synclinal basin, the southern boundary of which is marked by major faults. There are ten major seams in the Raniganj Formation, designated RI to RX. Their thicknesses range from 1 m to 11 m and the seams tend to thicken towards the east. There are seven major seams in the Barakar Formation, designated seams BI to BVII. These range in thickness from 1 m to 24 m, the lower seams generally being thicker. The Barakar seams are high in ash.

The coals seams generally dip to the south at angles between 3º and 11º. In places they are affected by igneous sills and dykes, which are more prominent in the Barakar seams, and by faults. About 22 billion tonnes of coal reserves were present in the field in 1993, and there were 109 collieries in operation, producing about 26 million tonnes of coal per annum (Coal Atlas of India, 1993).

THE JHARIA COALFIELD

This coalfield covers an area of 450 km^2 in the state of Bihar (Figure A2.1). The coalfield is a half-graben bounded to the SSW by a major fault. The coal-bearing formations dip SSW generally at 10º-15º but close to the bounding fault at up to 70º.

The Barakar Formation contains 18 coal seams (numbered I to XVIII) and the Raniganj Formation contains 12. Additionally there are a number of thin and impersistent seams. Barakar seams XIII and above are thin but of superior quality. The coal seams are affected in places by igneous dykes and sills and to varying degrees by faults.

This coalfield is the only source of prime coking coal in the country. In 1993, total reserves of coal were 19.4 billion tonnes, of which 5.3 billion tonnes were prime coking coal (Coal Atlas of India, 1993).

THE EAST BOKARO COALFIELD

This is located in the Damodar Valley in East Bihar (Figure A2.1). It is separated from the West Bokaro coalfield by Lugu Hill. It covers an area of 237 km^2. It is a major source of medium coking coal. It is a westwards-plunging syncline that is structurally disturbed by numerous faults that break it up into a number of smaller blocks with different geological characteristics and mining issues. The coal seams have been affected by igneous intrusives (dykes and sills) in places, particularly in the western part of the field.

There are three coal-bearing Formations; the Karharbari (4 seams), the Barakar (21 seams) and the Raniganj (8 seams). Coal rank increases with depth and also towards the east. The Kargali Seam is 20-50 m thick, contains only a few dirt bands and has superior coking coal properties. In 1993, total coal reserves were estimated to be 5.6 billion tonnes. There were 13 opencast and 10 underground mines operating in 1993, producing nearly 12 million tonnes of coal (Coal Atlas of India, 1993). The coalfield is an important source of medium coking coals. The Bokaro and Chandrapura power stations are nearby.

THE WEST BOKARO COALFIELD

This covers an area of 207 km^2 in the state of Bihar (Figure A2.1). It is narrowly separated from the East Bokaro Coalfield and the North Karanpura Coalfield, the latter lying immediately to the west, separated by a narrow belt of metamorphic basement rocks.

Structurally, the western part of the coalfield consists of two E-W trending synclines separated by a central antiform. These three features converge into a single syncline towards the eastern end of the coalfield. The coalfield is cut by numerous faults and coal seams have been affected by igneous dykes and sills in places, particularly in the Tapin and Parej blocks.

The main coal-bearing formations are the Karharbari and Barakhar formations. There are 13 major seams in the Barakar (29 seams in all) and one seam in the Karharbari. Total coal reserves were 4.6 billion tonnes in 1993, when there were 19 mines producing 3.5 million tonnes of coal per annum. Most of the coal production is opencast (Coal Atlas of India, 1993).

THE RAMGARH COALFIELD

This coalfield covers an area of 98 km^2 in the state of Bihar (Figure A2.1). The coal-bearing formation is the Barakar Formation.

Structurally, the coalfield is a half graben with major en-echelon bounding faults on its south side. It consists of two E-W-aligned sub-basins known as the main basin and the sub-basin. Dip usually varies from 10º to 12º in the Main basin and 10º to 20º in the Sub-basin. The coals are only slightly affected by dykes and sills in a few places.

The Barakar Formation contains 13 coal seams in the main basin and 11 coal seams in the sub-basin. Seams VIIIA, VIITop and VIIBottom are the most important seams and have moderate ash contents. A total of 970 million tonnes of coal reserves were estimated to be present in 1993, all at depths above 300 m. Production was about 2.9 million tonnes in 1993. All coal is produced by opencast methods (Coal Atlas of India, 1993).

THE SOUTH KARANPURA COALFIELD

This coalfield covers an area of 194 km^2 in the state of Bihar (Figure A2.1). Structurally it is a narrow elongated trough with a faulted southern boundary. The Bundu-Basaria metamorphic inlier is a major anticlinal feature that occurs towards the eastern end of the coalfield. The coalfield is cut by several faults and some of the seams have been affected by igneous intrusions (dykes and sills) in places.

The Barakar contains 10 coal horizons and there are two additional important seams in the underlying Karharbari Formation. The Raniganj Formation is present but contains no significant seams. The seams generally dip at 15º to 25º but steeper dips are occasionally present.

The coalfield had coal reserves of 5.7 billion tonnes in 1993, when 15 collieries were producing around 5.25 million tonnes coal per annum (Coal Atlas of India, 1993). The Patratu power station is located on the southern fringe of the coalfield.

THE NORTH KARANPURA COALFIELD

This coalfield covers an area of about 1230 km^2 in Bihar (Figure A2.1). Structurally the coalfield is a gently dipping elliptical syncline, with dips ranging from subhorizontal to about 10º. It is affected by a number of normal faults but is not significantly affected by the few dykes and sills that are present.

There are five standard coal horizons in the Barakar Formation and one localised seam in the Karharbari Formation. The Raniganj Formation is present but doesn't contain any significant coal seams.

The reserves of the coalfield were 13.6 billion tonnes in 1993. Production in 1992-3 was 8.14 million tonnes, of which 7.91 Mt was from opencast mines and 0.23 Mt was from three underground mines (Coal Atlas of India, 1993).

THE DALTONGANJ COALFIELD

This coalfield has a total area of about 250 km^2 in the state of Bihar (Figure A2.1). Structurally it is a narrow ESE-WNW-elongated basin. It comprises two sub-basins: the Rajhara/Lohari/Kathautia sub-basin in the north and the Singra-Meral sub-basin in the south.

The coal seams are all in the Karharbari Formation. The dip of the seams is generally from subhorizontal to 6º. There are a few igneous intrusions (dykes and sills) but these are not important. The coalfield is also faulted.

There are two main coal horizons containing up to 7 seams in the northern basin and five thin seams in the southern basin. The semianthracitic seams for which this coalfield is well known are found in Rajhara Colliery.

The total coal reserves in this field in 1993 were 0.14 billion tonnes, when the only active mine was Rajhara Colliery, with production of 0.39 Mt in 1992-3 (Coal Atlas of India, 1993).

THE HUTAR COALFIELD

This coalfield has an area of about 207 km^2 and is in the state of Bihar (Figure A2.1). Structurally it is a westerly-plunging E-W-elongated basin. The southern boundary of the field is marked by a major fault. The dip is generally 5º-15º but higher dips of up to 20º have been recorded. The seams are not affected by the few igneous intrusions (dykes and sills) in the coalfield.

The Karharbari Formation contains five significant coal horizons with low ash (Seams 1-5). Three or four impersistent coal seams are also present. The Barakar Formation does not contain significant coal seams.

Reserves were estimated at 0.25 billion tonnes in 1993, when 0.02 million tonnes were produced from underground mining at Hutar Colliery, the only operating colliery in the field (Coal Atlas of India, 1993).

THE SINGRAULI COALFIELD

The Singrauli coalfield covers an area of about 2200 km^2 in the northern most part of the Son-mahanadi Basin in the state of Madhya Pradesh (Figure A2.1). Only 300 km^2 in the NE part of the basin – the Moher sub-basin, is well explored. The rest is thought to have very limited economic potential. The Moher sub-basin is a half graben with a faulted northern margin. Dip typically varies from 3º to 5º but becomes steeper towards the northern boundary fault. There are no intrusions in the Moher sub-basin but it is cut by several faults. There are seams in both the Barakar and Raniganj formations. The Raniganj contains the thickest seam in the country, the 134 m Jhingurda seam. The Barakar contains eight coal horizons of which three are important. Most of the coal is high in ash and of power generation quality only. Total coal reserves were 9.21 billion tonnes in 1993, when 10 opencast mines were produced 30.7 million tonnes of coal in 1992-3 (Coal Atlas of India, 1993).

THE SOHAGPUR COALFIELD

This coalfield has an area of about 3000 km^2 and lies in Madhya Pradesh, in the Son-Mahanadi basin (Figure A2.1). Structurally it is divided into two parts by the Bamni-Chilpi Fault. All the coal seams are in the Barakar Formation. The number of coal seams varies across the basin; up to 14 seams are present in the Jhagraghand sub-basin. Known resources were 2.46 billion tonnes in 1993, when 28 underground mines and 5 opencast mines were in operation, producing 9.58 million tonnes of coal in 1992-3 (Coal Atlas of India, 1993).

THE KORBA COALFIELD

This coalfield occupies an area of about 520 km^2 in the state of Madhya Pradesh. It lies in the Mahanadi basin (Figure A2.1). Structurally the southern boundary of the basin is faulted-bounded. The dip generally varies between 2º and 8º. Faults are generally aligned E-W with subordinate faults in other directions. The coal seams are confined to the upper and lower parts of the Barakar Formation. These two zones are separated by a barren middle barakar section. The

Lower barakar contains 3-4 thin seams containing superior quality non-caking coal. The Upper Barakar contains up to 21 thick, interbanded inferior non-caking seams. In 1993 reserves were estimated at 9 billion tonnes. In 1992-3 27.11 million tonnes of coal were mined, comprising 23.55 Mt inferior and 3.56 Mt superior quality coals. Much of the coal goes to mine mouth power plants and the western India power plants (Coal Atlas of India, 1993).

THE IB RIVER COALFIELD

This coalfield occupies an area of about 1375 km^2 in the state of Orissa (Figure A2.1). Structurally the coalfield is a half-graben bounded to the SW by a large fault. The coal seams dip gently away from the field margins towards this fault and the basin centre. 6-7 coal horizons are present in the Karharbari and Barakar Formations, of which only two in the Barakar and one in the Karharbari have economic potential. The Barakar coals vary from 20 to 60 m in thickness. They are banded, have high ash content, high moisture and volatile content and are of low rank. The Karharbari seam is 1 to 7 m thick and generally of better quality.

In 1993, reserves in the field were 20.81 billion tonnes. In 1992-3 7.8 million tonnes of coal were mines, mainly from opencast pits. The coalfield is a major supplier to the western India power stations (Coal Atlas of India, 1993).

THE TALCHER COALFIELD

This coalfield occupies an area of about 1815 km^2 in the state of Orissa (Figure A2.1). Only the eastern part, about 400 km^2 in size contains exposures of coal-bearing Karharbari and Barakar Formations. Structurally it is a broad synclinal basin with dips of around 3º to 7º. The degree of faulting varies across the field. There are no igneous intrusives (dykes and sills) in the coalfield. There are up to 12 seams in the Barakar and one in the Karharbari. They vary in thickness from 1 to 60 m. All except seam 1 are of low quality (F-G grade), being interbanded, with high ash content, high volatile and high moisture content. The only good quality seam is Seam 1, in the Karharbari, which has ash content <20% (Coal Atlas of India, 1993).

THE PENCH-KANHAN-TAWA VALLEY COALFIELD

This coalfield occupies an area of about 600 km^2 in Madhya Pradesh (Figure A2.1). It forms the southern fringes of the Satpura Basin. It can be divided into three parts: Pench, Kanhan and Tawa. The coalfield has a high degree of structural disturbance, particularly in the Pench-Kanhan Valley.

Up to five seams are present in the Pench are, but these deteriorate westwards until only one with any economic importance is present in much of the Kanhan valley. The coals in the Pench area are generally of low rank but in the western part of the Kanhan area rank improves. In the Tawa Valley there are 2-4 seams with economic potential. The upper two seams are generally of inferior grade whereas the highest one has lower ash. In 1993 reserves were estimated at 2.369 billion tonnes. There were 24 mines in the Pench-Kanhan valley, producing 3.6 million tonnes of coal in 1992-3. In the Tawa valley, 7 mines produced 2.47 million tonnes of coal in 1992-3 (Coal Atlas of India, 1993).

THE WARDHA VALLEY COALFIELD

This coalfield covers an area of about 4130 km^2 in the state of Maharashtra (Figure A2.1). About 620 km^2 is considered to have economic potential at present. Some of the remainder may contain concealed Coal Measures at depth. The degree of faulting in the productive area is low and dips generally vary between 3º and 11º. A single seam, which varies in thickness between 10 and 20 m, occurs over most of the coalfield, although it splits into two in several places. It is highly banded, of low rank and is high in moisture and ash.

In 1993, reserves were estimated at 4.42 billion tonnes. In 1992-3, 15.26 million tonnes of coal were produced, largely from opencast mines. The coalfield feeds the pithead power stations at Chandrapur (Coal Atlas of India, 1993).

THE RAJMAHAL GROUP OF COALFIELDS

This group of coalfields consists of five relatively small coal basins (Hura, Chuperbhita, Pachwara, Mahuagarhi and Brahmani) exposed along the western flank of the Rajmahal Hills (Figure A2.1). In general, the beds dip 5º to 10º to the east, and the coal-bearing formations extend below the Rajmahal traps to the east. The coals are of low rank and high ash content (up to 545). In 1993 reserves were estimated to be 11 billion tonnes of which about 2 billion tonnes are proven. Only the Hura and Chuperbhita fields are mined – the others are untouched. Hura is an important field, producing 3.9 million tonnes in 1992-3 (Coal Atlas of India, 1993).

THE GODAVARI VALLEY COALFIELD

This coalfield covers an area of about 17000 km^2 in Andhra Pradesh (Figure A2.1). It consists of discontinuous patches of Coal Measures occurring in the Godavari rift basin. The Barakar Formation contains 3-10 coal seams of which four or five are usually persistent and workable. The coals have high ash and high volatile matter and are of low rank. Generally the lower seams are of better quality. Total reserves were estimated to be 10.8 billion tonnes in 1993, of which 6.1 billion tonnes are considered proved (Coal Atlas of India, 1993).

COALFIELDS IN NORTH-EASTERN INDIA

Although most are very small, there are 67 individual coal fields in the states of Assam, Arunachal Pradesh, Nagaland and Meghalaya (Figure A2.1). These can be divided into: isolated small Gondwana coal deposits along the foothills of the Himalaya (which are not economically important) and at Singrimari in Assam/Meghalaya; Eocene coal deposits along the southern margin of the Mikir Hills and Meghalaya; and Oligocene coal deposits in the thrust belt along the southern side of the Assam valley. Generally, all these coal seams are <1 m thick. They are low in ash (<15%) high in volatile matter and high in sulphur (2-6%).

Total reserves in the northeast region were estimated in 1993 to be 865 million tonnes (Coal Atlas of India, 1993). In terms of production, the most important of these fields is the Makum coalfield in southern Assam.

Appendix 3 Brief descriptions of the CO_2 storage potential of the sedimentary basins of India, Pakistan and Bangladesh

The sedimentary basins are described below in alphabetical order.

THE ASSAM BASIN

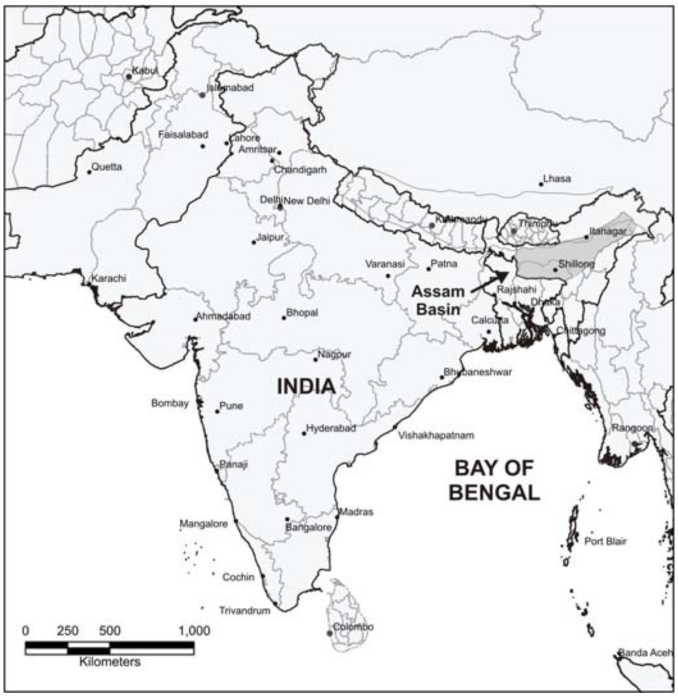


Figure A3. 1 Location of the Assam Basin

Introduction

The Assam Basin (Figure A3.1) covers an area of around 56,000 km^2. It is bounded by thrust belts to the north, northeast and southeast, and by the Mikir Hills and Shillong Massif to the southwest (Figure A3.2). It is sometimes referred to as the Assam Shelf, because the rocks within it were deposited in shallow marine to alluvial settings.

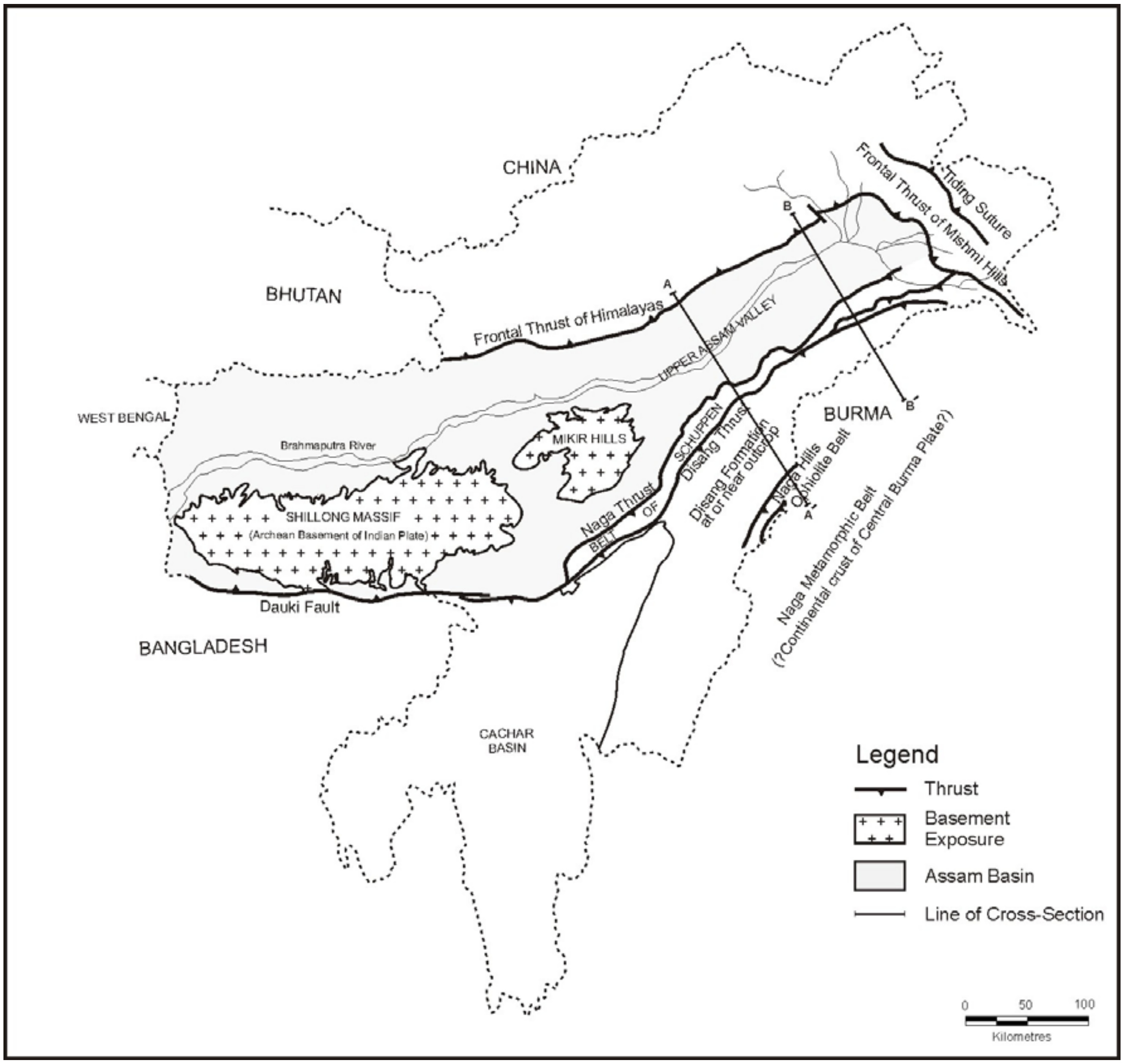


Figure A3. 2 Location map of Assam Basin and Northeast India, including major faults and geological formations

Tectonic & Structural Setting

The Assam basin is bounded to the northwest by the Main Himalayan Boundary Thrust, to the northeast by the Mishmi Thrust and to the southeast by the Naga and Disang Thrusts. The area between the Naga and Disang thrusts, which contains other thrusts such as the Margherita Thrust, is known as the Belt of Schuppen. To the southwest, the basin is shallows towards, and is bounded by, the Precambrian rocks of the Mikir Hills and Shillong Massif. To the north of the Shillong Massif, the basin merges with the northernmost part of the Bengal Basin north of the Rangpur Saddle in NW Bangladesh

The current configuration of the basin is due to a combination of the regional north-northeast drift of the Indian plate beneath the Himalayan Boundary Thrust and Mishmi Hills Thrust and westward overriding of the basin by the Burmese plate, which has resulted in the development of NW-oriented Naga and Disang thrusts and the other thrusts within the Belt of Schuppen.

NW-SE-oriented compression, arising from displacements of opposite direction on the Naga Hills and Himalayan thrust belts (Das, 1992), has gently folded the basin into a broad arch known as the Brahmaputra Arch (Figure A3.3). This structure affects both the Basement and

Cenozoic strata of the Upper Assam Valley and its axis runs parallel with the Brahmaputra River. It dips off towards the northwest and southeast, and has been dissected by a number of faults (Murty, 1983).

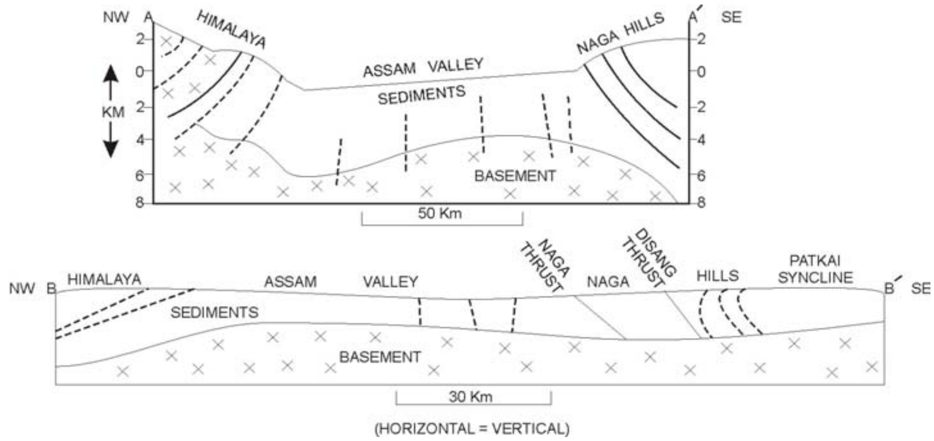


Figure A3. 3 Cross sections through the Assam Basin. See Figure 1 for cross section locations. After Das (1992)

Active Tectonism

The sedimentary rocks within the basin have been disturbed in the recent past by two very large earthquakes - in 1897 and 1950. The great Assam earthquake of 12 June 1897 reduced to rubble all masonry buildings within a region of north-eastern India roughly the size of England, and was felt over an area exceeding that of the great 1755 Lisbon earthquake. The northern edge of the Shillong plateau rose violently by at least 11m. This was due to the rupture of a buried reverse fault approximately 110 km in length on the north side of the Shillong Plateau (Billam and England, 2001).

One of the largest earthquakes recorded seismographically was the magnitude 8.6 or 8.7 Assam event in 1950, which caused ground upheaval and many rock falls in the Mishmi Hills. In the Arbor Hills, 70 villages were destroyed with 156 casualties due to landslides. Rock falls blocked the tributaries of the Brahmaputra. The rockfall damming the river in the Disang valley subsequently broke without causing damage, but one at Subansiri opened after an interval of 8 days causing a wave 7 metres high that submerged several villages and killed 532 people.

Future large-scale earth movements could potentially cause 'catastrophic' modification of the basin, reactivating the existing fracture zones in the Itanagar region (Das, 1992).

Stratigraphy

In the Upper Assam Valley, 0-7 km of mainly terrigenous Cenozoic sediments overlie a Precambrian metamorphic/igneous basement. The thickness of the sedimentary cover increases from zero at the Mikir Hills in the southwest to >7 km near the northeast margin of the basin (Bhandari et al. 1973).

Basement rocks

The Precambrian basement consists mainly of crystalline metamorphic rocks, including biotite gneiss, pink granites & quartzites (Bhandari et al. 1973).

Basin fill

Palaeozoic-Mesozoic strata could be present within the Subansiri and Luhit depressions on the NW margin of the Assam Basin, just in front of the Himalayan foothills (Bhandari et al., 1973), but no evidence such strata has yet been discovered (Acharyya et al. 1975) so it is likely that the basin fill is entirely Cenozoic in age, and major basin subsidence commenced during Palaeocene times.

The Cenozoic sequence is divided into two supergroups separated by a major unconformity (Figure A3.4, see also Wandrey 2004). The Naga supergroup consists of Palaeogene sediments deposited in shallow marine-paralic environments. It is further divided into the Jaintia and Barail groups. The overlying Brahmaputra supergroup consists mainly of fluvial and deltaic sediments that are Neogene in age, and are sub-divided into the Surma, Tipam and Moran groups (Bhandari et al. 1973).

AGE	SUPERGROUP	GROUP	FORMATION	THICKNESS RANGE (M)		LITHOLOGY
PRE HOLOCENE - HOLOCENE		ALLUVIUM		300-650		
LATE PLIOCENE - PLEISTOCENE	BHRAMAPUTRA	MORAN	DHEKIAJULI	420-1080		
LATE MIOCENE - MIDDLE PLIOCENE			NAMSANG	250-520		
MIDDLE MIOCENE		TIPAM	NAZIRA SS.	340-1710	0-580	
			GIRUJAN CLAY		0-850	
		Surma	LAKWA SS.		160-550	
EARLY MIOCENE		SURMA	GELEKI SS.	200-780		
OLIGOCENE	NAGA	BARAIL	RUDRASAGAR	290-740	30-520	
			NAOGOAN SS.		180-670	
LATE EOCENE		JAINTIA	KOPILI	350-460		
MIDDLE EOCENE			SYLHET LS.	90-270		
CRETACEOUS - EARLY EOCENE			LANGPAR TEOK DISANG	12-90		
ARCHAEAN	METAMORPHIC AND IGNEOUS ROCKS					

Figure A3. 4 Stratigraphy of the Assam Basin, based on Bhandari et al. (1973)

Hydrocarbons

Oil seeps were known in Assam as early as 1825. The first commercial discovery was at Digboi in about 1899 and a refinery had been established there by 1901.

Between 1922 and 1932 Burmah Oil Co. drilled ten structures in the Belt of Schuppen without success. Oil India Ltd (OIL) first discovered oil in the Nahorkatiya field in 1953 and then in 1956 in the Moran Group in the Moran Field. Significant discoveries by ONGC followed during the period 1960-1971 (Murty, 1983).

By 1975, around 500 deep wells had been drilled in the region by OIL and the ONGC (Bhandari et al., 1973). By 1983, due to the discovery of productive pre-Barail sandstone/limestone horizons in the Borholla region south of the Mikir Hills (Murty 1983), almost forty wells had been drilled through the pre-Barail sequence in this area by ONGC (presumably to basement although this is not specified).

The distribution of discoveries strongly suggests that the petroleum source rocks are mature beneath the Naga Thrust and that petroleum is migrating northwards onto the southern flanks of the Brahmaputra arch, i.e. that part of the basin south of the Brahmaputra river. There are no discoveries north of the Brahmaputra River.

Reservoir rocks and seals

The bulk of the oil production in Assam is from the Oligocene Barail Formation and the Miocene Tipam Formation (Raju & Mathur, 1995). Local porosity/permeability variations, and the lenticularity of sand bodies, are key factors controlling the accumulation of hydrocarbons within the Barail (Murty, 1983).

The Tipam Formation has a permeability range of <8-800 mD, and a porosity range of <7-30%. The Girujan Formation represents an effective sub-regional scale seal over the Tipam Formation. It is generally >200 m thick but thins to ~50 m over structural highs.

Thin sandstone beds within the Upper Palaeocene-Lower Eocene shales of the Langpar Formation and the Lakadong Member of the Sylhet Formation may also have potential as reservoir rocks (Mallick & Raju, 1995). Strata overlying the Langpar Formation include shales, silts and marls, reaching thicknesses of up to 800m, and would likely provide adequate seal potential.

According to Murty (1983), the northern part of the Brahmaputra valley has very poor hydrocarbon prospects because the thinning of sedimentary sequences has resulted in ineffective cap rocks (this could provide an explanation for the absence of oil and gas discoveries north of the Brahmaputra, although, alternatively, petroleum migration from beneath the Naga Thrust may not have reached across the Brahmaputra Arch). If Murty is correct the area north of the Brahmaputra also will have poor CO_2 storage potential.

CO_2 Storage Potential

The presence of oil fields in the area south of the Brahmaputra River, at several stratigraphic levels in the Cenozoic section, indicates that this part of the Assam Basin has good potential to store buoyant fluids such as supercritical CO_2. Several apparently well-sealed reservoir horizons are present. However, there are many abandoned wells in the area, some of which might have to be considered in any storage project.

However, the area is remote from the main part of peninsula India and thus would best provide storage potential for local CO_2 sources. Any CO_2 transport to Assam from peninsular India would have to be by pipeline around the ‘chicken neck’ to the north of Bangladesh, across Bangladesh, or across Bangladeshi territorial waters. The area is also prone to some of the largest earthquakes ever recorded.

References

Acharyya, S.K., Ghosh, S.C. & Ghosh, R.N. 1975. ‘Stratigraphy of Assam Valley, India: Discussion.’ *Bulletin American Association of Petroleum Geologists*, **59** (10), 2046-2057.

Bhandari, L.L., Fuloria, R.C. and Sastri, V.V. (1973) ‘Stratigraphy of Assam Valley, India.’ *American Association of Petroleum Geologists Bulletin*, **57**(4), 642-654.

Billam and England (2001)

DAS, J.D. 1992. The Assam Basin: Tectonic Relation to the Surrounding Structural Features and Shillong Plateau. *Journal Geological Society of India*, **39**, 303-311.

Mallick, R.K. and Raju, S.V. (1995) ‘Application of Wireline Logs in Characterization and Evaluation of Generation Potential of Palaeocene-Lower Eocene Source Rocks in Parts of

Upper Assam Basin, India.' In: Swamy, S.N. and Dwivedi (eds.) *Second International Petroleum Conference: Petrotech-97, 9-12 January, 1997.* **1**, 49-63.

Murty, K.N. 1983. Geology and Hydrocarbon Prospects of Assam Shelf – Recent Advances and Present Status. *Petroleum Asia Journal.*

Raju, S.V. & Mathur, N. 1995. 'Petroleum geochemistry of a part of Upper Assam Basin, India: a brief overview.' *Organic Geochemistry*, **23**(11), 55-70.

Rangarao, A. 1983. Geology and Hydrocarbon Potential of a part of Assam-Arakan Basin and its Adjacent Region. *Petroleum Asia Journal*, November 1983, 127-158.

Wandrey, C.J. 2004. 'Sylhet-Kopili/Barail-Tipam Composite Total Petroleum System, Assam Geologic Province, India.' In: Wandrey, C.J. (ed.), *Petroleum Systems and Related Geologic Studies in Region 8, South Asia.* USGS, 1-19.

THE ASSAM-ARAKAN FOLD BELT

Introduction

The Assam-Arakan Fold Belt (Figure A3.5) runs roughly N-S along the eastern margin of the Bengal Basin, west of the Burmese ranges, through the Indian states of Tripura, Mizoram, Manipur and Cachar, and, in Bangladesh, through the Chittagong Hill Tracts and the easternmost part of the Surma basin.

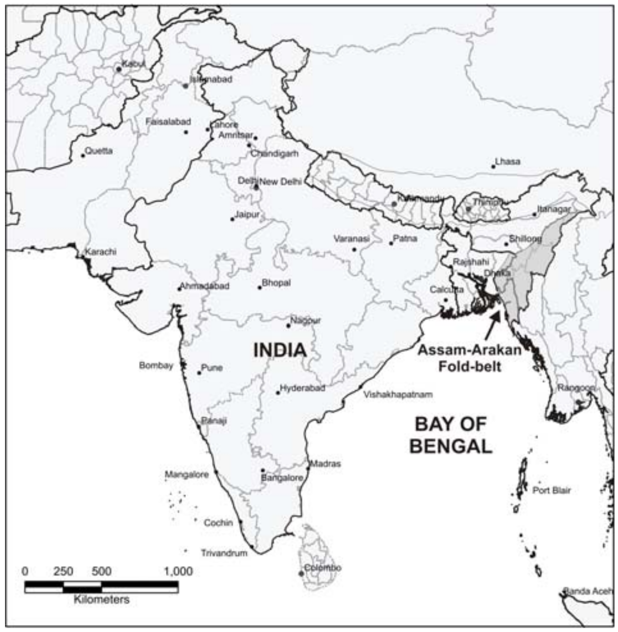


Figure A3. 5 Location of the Assam-Arakan Fold Belt in NE India and Bangladesh

The fold belt comprises the easternmost part of the Bengal Basin and therefore contains a very thick Cainozoic sedimentary succession (Aubouin 1965, Ganguly 1983). The fold belt has been formed by oblique collision between the Indian and Burmese continental plates from Oligocene times onwards, which continues to the present day. In broad terms, the folds increase in amplitude and intensity from west to east towards the Burmese Ranges, beneath which it is thought that the basin is being subducted.

Generally, the elevation of the region increases eastwards from eastern Bangladesh and Tripura through Mizoram and Manipur towards the Chin Hills of Burma. Concomitantly, the rocks and folds exposed in the eastern part of the fold belt are in general older than those in the western part. As a whole, the exposed rocks in the Tripura-Mizoram-Manipur belt range in age from Late Mesozoic in the east to Palaeogene, Neogene and Recent in the west (Ganguly, 1983).

The region is geographically remote and poor accessibility means that there has been relatively little hydrocarbon exploration in the region, given that it is folded into a number of prominent anticlines oriented approximately N-S. These folds are very clearly visible, and mappable, on satellite images of the region.

Structure

The region comprises a series of subparallel, arcuate, elongated, doubly plunging en-echelon folds trending in an average North-South direction.

A slight convexity of the folds towards the west is seen (Ganguly, 1983). From east to west, the deformation seen in the fold belt becomes progressively younger and less intense. The Tripura and Cachar areas contain younger ‘narrow, box-like’ anticlines separated by ‘wide, flat’ synclines, while the Mizoram area consists of tight, linear synclines (Ganguly, 1983). The structural patterns observed in the Tripura and Cachar regions are diagnostic of basement-involved compressive block-fault styles, which merge into wrench-like features in some places. The structures seen in Mizoram (on the eastern side of the fold belt) appear to grade into detached thrust/fold assemblages.

Stratigraphy

The lithostratigraphy of the Tripura-Manipur region, as presently understood, is illustrated in Figure A3.6. However, it should be borne in mind that the exposed Neogene strata of NE Bangladesh and the Tripura-Cachar-Mizoram region of NE India, which are composed mainly of alternating shales, mudstones, siltstones and sandstones (Ganguly, 1983) were deposited by the Brahmaputra river and its predecessors draining the rising Himalayan mountains. Thus they were deposited in a major outwash area, largely in alluvial and deltaic environments, in a tectonically unstable, rapidly subsiding, basin (Ganguly 1983). They are very difficult to subdivide lithostratigraphically as similar facies of varying age are present within the succession. A sequence stratigraphic subdivision, as attempted by Lindsay et al. 1991) in NW Bangladesh, could prove productive, at least in the less structurally complex western parts of the fold belt.

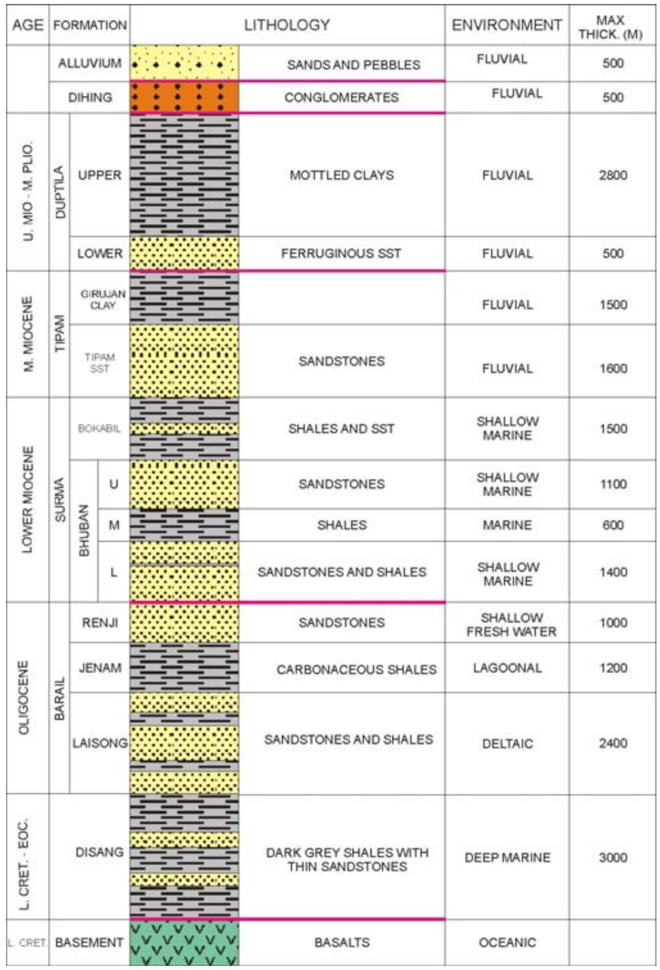


Figure A3. 6 Lithostratigraphy of the Tripura-Manipur region

A characteristically monotonous argillaceous sequence known as the Disang Shales is exposed in an extensive area south and southeast of the Disang Thrust, in Assam, Cachar, Manipur, Mizoram and parts of Burma southeast of the Naga Hills. The Disang Shales are thought to be approximately 2000 m to 3000 m thick (Banerji, 1979). Despite some scattered gas seeps, this sequence is thought to have poor hydrocarbon prospects due to the lack of reservoir rocks.

To the west of their outcrop, the Disang Shales are overlain by the younger Barail-Surma-Tipam sedimentary sequences.

The rocks exposed in the anticlinal cores in the central and western parts of the fold belt are believed to be equivalents of the Mio-Pliocene Surma Group. They are about 4000 m thick in Tripura, and around 7000 m thick in Mizoram. At least three major transgressive marine cycles are present (Ganguly, 1983). The Surma Group is conventionally further divided into the lower Bhuban unit (more arenaceous), and the upper Boka Bil unit (mainly argillaceous).

The Tipam Group (as seen in the neighbouring Assam Valley) is thought to be represented in the younger arenaceous beds on the flanks of the anticlines, which are Pliocene in age and are >2000 m thick. Sedimentological evidence suggests that parts of the Tipam Group in northern Cachar were deposited under the influence of a tidal regime (Rangarao, 1983). In general however, the sequences of the Tipam (and overlying Dupi Tila) group were deposited under subaqueous-subaerial, fluviatile-lacustrine conditions (Ganguly, 1983).

CO_2 storage potential

Gas fields are present in the outer parts of the fold belt, e.g. in the Surma Basin (eastern part of the Bengal Basin, NE Bangladesh), the Chittagong Hill Tracts (SE Bangladesh), Tripura and Mizoram. The presence of the Surma, Barail and Tipam groups in the Cachar-Tripura-Mizoram region, all of which contain sandstones, suggest that potential for aquifer CO_2 storage exists in these areas as well, at least west of the outcrops of Disang Shales. However, overpressure, encountered in drilling operations in the fold belt, may be an issue. The main drawback is geographic: the Indian parts of the fold belt are remote from both major CO_2 sources and the main part of India,

References

Aubouin, J. 1965. '*Geosynclines*.' Elsevier Publishing Company, Amsterdam. 335 pp.

Banerji, R.K. 1979. 'Disang Shale, its Stratigraphy, Sedimentation History and Basin Configuration in North-eastern India and Burma.' *Quarterly Journal of the Geological, Mining and Metallurgical Society of India*, **51**, 133-142.

Ganguly, S. 1983. Geology and Hydrocarbon Prospects of Tripura-Cachar-Mizoram Region. *Petroleum Asia Journal*. Nov. 1983, 105-109.

Lindsay, J.F., Holliday, D.W. & Hulbert, A.G. 1991.'Sequence Stratigraphy and the Evolution of the Ganges-Brahmaputra Delta Complex. *Bulletin American Association of Petroleum Geologists,* **75**(7), 1233-1254.

Rangarao, A. 1983. Geology and Hydrocarbon Potential of a part of Assam-Arakan Basin and its Adjacent Region. *Petroleum Asia Journal*, November 1983, 127-158.

THE BALOCHISTAN BASIN

The Balochistan Basin (Pakistan) covers an area of over 300,000 km^2 (see Figure 0.2 for location). From an oil and gas perspective, this basin is the least explored basin in Pakistan. Only six wells had been drilled up to 1997 (of which one was offshore) and, despite several gas shows along the Makran coast, no commercial discoveries have been made.

Structurally, the basin extends offshore, where it is bounded to the south by the Makran offshore trench. To the east it is bounded by the Chaman Transform Zone. To the north it is bounded by the Chagai Volcanic Arc and to the west it extends into Iran. The basin is described in detail by Kadri (1995).

Geologically it comprises an Arc-Trench system. At its southern margin (offshore) the Arabian Oceanic Plate is being subducted beneath the margin of the Eurasian Continental Plate. From south to north the basin can be subdivided into the Makran Tranch, Coastal Makran Depression, Makran Accretionary Prism, Kharan Forearc basin, an inter-arc region and the Chagai Volcanic Arc (see Kadri 1995 for details).

The basin contains 5000 – 15000 m of flysch-type terrigenous slope and shelf sediments and turbidites. All the drilling activity to date has been in the Makran Accretionary Prism, close the coast. This area is structurally complex. There is no shortage of reservoir rocks, but overpressure has proved an operational problem, and this may reduce its potential for CO_2 storage.

Because it contains no proven oil and gas fields at present, and is comparatively poorly explored, it is classified at present as having limited potential for CO_2 storage. Further research could enhance our perception of its potential however.

References

Kadri, I.B. 1995. *Petroleum Geology of Pakistan*. Pakistan Petroleum Ltd, Karachi, 275 pp.

THE BARMER BASIN

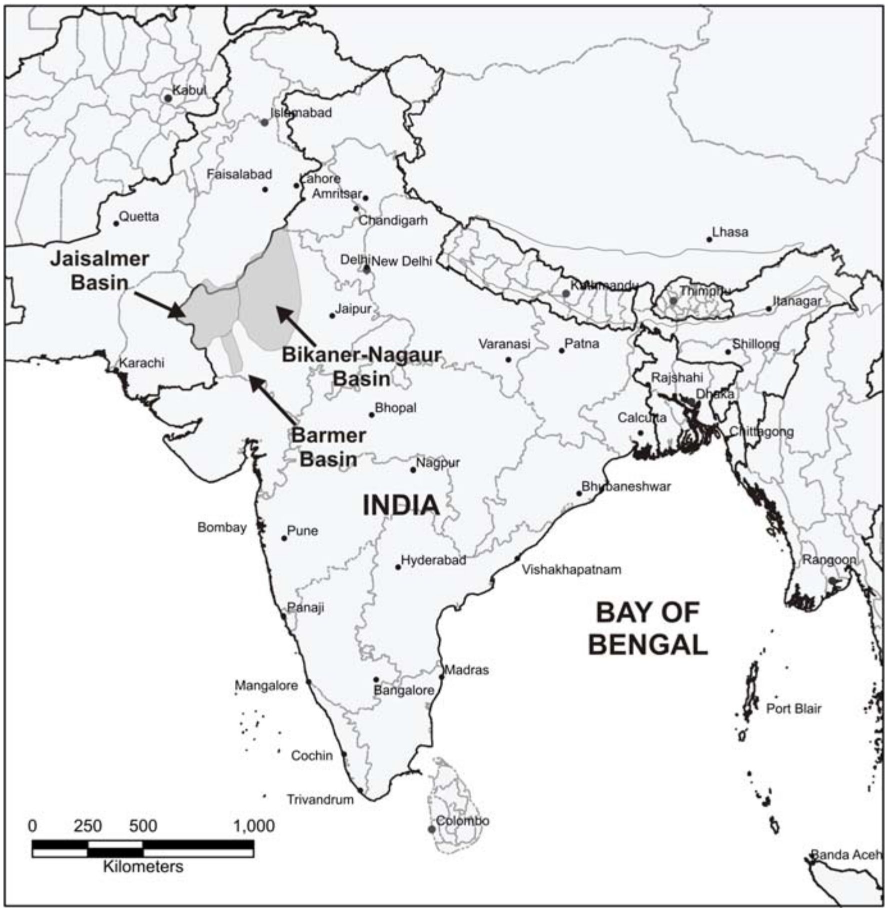


Figure A3. 7 Location of the Barmer Basin

Structure

Geologically, the Barmer Basin is the northernmost segment of the Cambay graben but it is commonly described separately from the Cambay Basin because it is in Rajasthan rather than Gujarat. Structurally it is a narrow N-S-oriented fault-bounded graben. The faulting on its eastern side upthrows basement rocks to outcrop. It is separated from the Jaisalmer Basin, to the north, by the Fateghar Fault, immediately north of which lies the Devikot-Nachna High (Figure A3.7). It appears to be contiguous with the Sanchor depression in the Cambay Basin, immediately to the south.

Stratigraphy

According to Mohan & Sangai (1995), the stratigraphy of the Barmer Basin shows greater similarity to that of the Jaisalmer Basin than the Cambay Basin. At the base of the basin is a Proterozoic succession consisting of the Randha Formation unconformably overlain by the Birmania Formation. A Jurassic succession (comprising the Lathi Formation overlain by the Jaisalmer Formation) overlies this. Above the Jurassic is the Early Cretaceous Sarnu Formation, which is overlain by over 500 m of marine and continental Cretaceous-Eocene strata (Dhar et al., 1974; Pareek, 1976; Khar, 1984), above which is Pleistocene-Recent alluvial cover.

The Proterozoic and Jurassic formations in the Barmer graben are also found in the Jaisalmer Basin to the NW.

Hydrocarbons

Cairn Energy has made several large oil discoveries in the Barmer Basin in recent years. To date over 2 billion barrels of oil in place and an as yet undetermined volume of gas have been discovered by Cairn, in a variety of reservoirs in the basin.

CO_2 storage potential

There is likely to be excellent future potential for CO_2 storage in the Barmer Basin, both for EOR in the oil fields once these are developed, and in the aquifers. Projected secondary recovery by waterflooding in the main fields is predicted to be only in the order of 9-30% of STOIIP.

THE BENGAL BASIN

Figure A3. 8 Location of the Bengal Basin

The Bengal Basin lies in NE India and Bangladesh (Figure A3.8). It covers, in India, an area of 57,000 km^2 onshore and 32,000 km^2 offshore. It also covers all of Bangladesh apart from the extreme NE and the Chittagong Hill Tracts, which are here included in the Assam-Arakan Fold Belt.

The Bengal Basin is bounded by the Indian shield to the west. To the north it is bounded by the basement rocks of the Shillong Plateau and shallow concealed basement under the Rangpur Saddle in northern Bangladesh.

The basin itself extends eastwards from the Rajmahal coalfields and Rajmahal Traps of West Bengal across Bangladesh. The eastern margin of the basin is folded and forms part of the Assam-Arakan Fold Belt, which runs roughly N-S through the Indian states of Tripura, Mizoram and Cachar, and the Chittagong Hill Tracts of Bangladesh. The Assam-Arakan fold belt is described separately above.

The sedimentary rocks and sediments filling the basin are mostly Cenozoic to Recent in age. However, Permian and Mesozoic rocks underlie the Cenozoic in places.

Tectonic and Structural Setting

Tectonically, the Bengal Basin is a passive margin basin which, since Oligocene times, has been filled with sediment derived from the Himalayas, most of which was transported into the basin by the Ganges and Brahmaputra rivers and their predecessors.

The eastern part of the basin (in eastern Bangladesh, Tripura, Cachar and Mizoram) is folded into a series of anticlines and synclines arising from eastwards-directed subduction of the eastern basin margin beneath the Burmese ranges. The western part of the basin (the main Indian part and western Bangladesh) is not significantly folded and, east of the western basin margin fault zone, the strata simply dip homoclinally east and southeast into the Bay of Bengal. The southern part of the basin spills southwards off the continental crust onto ocean crust at the bottom of the Bay of Bengal, where it forms a huge ocean-bottom fan.

On the western side of the basin, four tectonic zones are recognised (Mukherjea and Neogi, 1993). Raman (1986) shows the location of these tectonic zones and important well locations:

- The basin margin fault zone,
- Shelf/platform,
- Shelf/slope break and
- Basin deep

Basin Margin Fault Zone

The NNE to SSW-trending basin margin fault zone differentiates an area of shallow crystalline metamorphic basement from the Shelf area. It is truncated to the north by shallow basement ridges that were uplifted during the Mid Miocene and subsided again during the Pliocene.

Shelf Area

The western foreland shelf extends from the Basin Margin Fault Zone to the Eocene hinge zone. The shelf dips gently and homoclinally to the east, and is cut by numerous 'down to basin' faults with small down-ESE displacements. Sedimentary sections thicken down dip, and additional marine wedge-shaped sequences develop in the down-dip direction (Mukherjea & Neogi, 1993).

Hinge Zone

This zone separates the western foreland shelf from the basin deep to the east and south. It is defined by a moderate down-ESE flexure in the Sylhet Limestone. The Sylhet Limestone reaches its maximum thickness of 700-1000 m in this zone (Mukherjea & Neogi, 1993).

Basin Deep

This comprises a sedimentary prism 10-15 km thick. Drilling has not yet reached below the Upper Oligocene. Seismic reflection surveys show that the prominent reflector at the top of the Sylhet Limestone loses its definition in the basinal area, possibly due to facies change (Mukherjea & Neogi, 1993).

Stratigraphy

The Bengal Basin is principally a Cenozoic basin. However, the earliest sedimentary rocks in the basin are Gondwana Supergroup strata - mainly coarse arkosic continental facies, but including some coal-bearing sequences, see Figure A3.9. These were eroded from most of the basin during the Mesozoic but are preserved in small, downfaulted grabens in the basement, particularly beneath the Bangladeshi part of the basin. Here coal-bearing sequences form the Jamalganj, Khalaspir and Barapukuria concealed coalfields. Further shallow coal deposits that may eventually be worked by opencast methods are present in the extreme north of the basin. Coal was also found at depth in the Bogra 1 well in Bangladesh.

On the western margin of the basin, basaltic and andesitic lava flows (the Rajmahal Traps) covered the basement and the patchily distributed Gondwana sediments during Late Jurassic – Early Cretaceous times. The eruption of the Rajmahal Traps was most likely associated with the fragmentation of Gondwana and the separation of the eastern margin of the Indian plate from Antarctica and Australia.

The first marine transgression onto the newly formed eastern passive margin of India took place during the Campanian. This marine transgression is represented by the Dhanjaypur Formation (Das and Baq, 1996). The Campanian strata are followed by coarsening upwards successions of clastics - the Bolpur, Ghatal and Jalangi formations of Maastrichtian to Palaeocene age.

The flux of clastic sediments into the basin was drastically reduced during Eocene times, when the basin became a carbonate platform. This period is represented by the (relatively thick) Sylhet Limestone Formation, which is overlain by the (relatively thin) Kopili Shales (Das and Baq, 1996). The Sylhet Limestone is one of the most prominent regional seismic markers. It also occurs in the Mahanadi Basin to the south and the Assam Basin to the NE.

The post-Eocene succession in the Bengal Basin represents the alternating progradation, erosion and transgression of vast alluvial systems resulting from the erosion of the rising Himalayan Mountains (Lindsay et al. 1991). Huge amounts of sediments continued to be deposited today, by the Ganges – Brahmaputra – Meghna river systems, creating one of the world's biggest modern delta systems and the giant Bengal Fan (Curray, 1994).

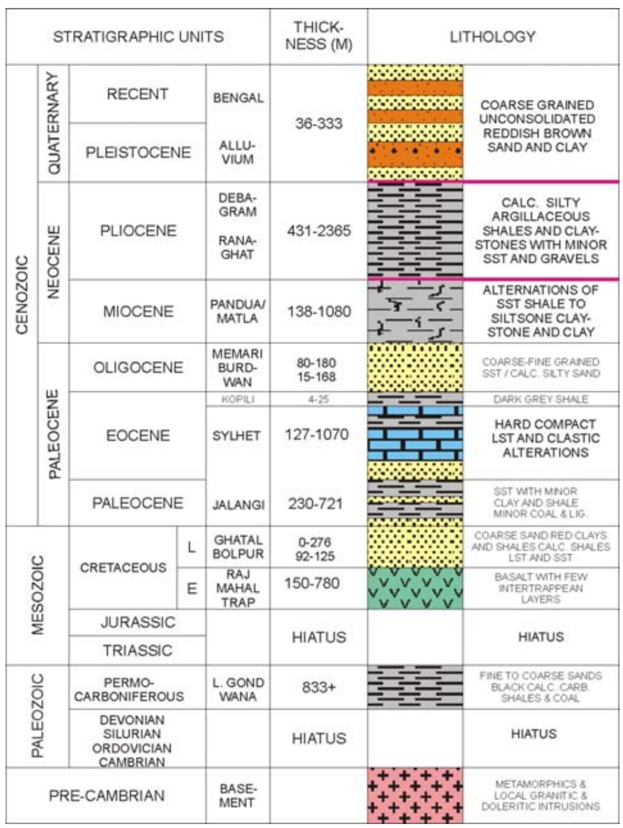


Figure A3. 9 Outline lithostratigraphy of the Bengal Basin, adapted from Mukherjea & Neogi (1993)

Hydrocarbons

Hydrocarbon exploration in the Indian part of the Bengal Basin was started in the late 1940s by the Standard Vacuum Oil Company and continued into the 1950s via the Indo-Stanvac Petroleum Project (ISPP). Thereafter, ONGC continued exploration activities on its own. There has been little success to date in the Indian and western Bangladesh parts of the basin. However, there have been several major gas discoveries in the eastern part of the basin, in Bangladesh, where anticlines are present. Recently there have been potentially significant gas discoveries in the Upper Miocene offshore close to the boundary between the Mahanadi and Bengal basins, see http://www.dghindia.org/site/pdfattachments/e_p_reports_2005_06.pdf. If significant, these could have profound implications for the prospectivity of the SW part of the Bengal Basin.

Reservoir rocks and seals

Sandstone reservoir rocks are present in the Oligocene and younger strata, although seals are not proven in the western part of the basin.

Structural closure

There is a lack of well-defined structural closure in the western part of the basin. However, anticlines are well developed in the eastern half of the basin, in Bangladesh, Tripura and Mizoram.

Overpressure

Overpressurisation, caused by rapid Neogene sedimentation (Mukherjea & Neogi, 1993), occurs east of the hinge zone and could be an issue for CO_2 injection.

Summary of CO_2 Storage Potential

Onshore, the western Bengal Basin may have some CO_2 storage potential, but the lack of proven seal and closure means that prospects are classified as limited. Offshore, the south-western Bengal Basin may have good potential if the recent gas discoveries prove significant gas columns can exist. There is excellent potential in eastern Bangladesh, where there are gas fields in the basin both onshore and offshore.

References

Curray, J.R. 1994. Sediment volume and mass beneath the Bay of Bengal. *Earth and Planetary Science Letters,* **125**, 371-383.

Das, S.K. & Baq, S. 1996. Types and Distribution of Stratigraphic Plays in Post-Trappean Sequence of the Bengal Basin, India. Oil and Natural Gas Corporation Limited, India. pp. 14

Lindsay, J.F., Holliday, D.W. & Hulbert, A.G. 1991.'Sequence Stratigraphy and the Evolution of the Ganges-Brahmaputra Delta Complex. *Bulletin American Association of Petroleum Geologists,* **75**(7), 1233-1254.

Mukherjea, A. & Neogi, B.B. 1993. 'Status of Exploration in Bengal Basin, West Bengal, India.' In: Biswas, S.K., Dave, A, Garg, P., Pandey, J, Maithani, A., Thomas, N. J. (editors), *Proceedings Second Seminar on Petroliferous Basins of India*, **Vol 1**. Indian Petroleum Publishers, Dehra Dun, India, 93-119.

Raman, K.S., Kumar, S. & Neogi, B.B. 1986. 'Exploration in Bengal Basin India – An Overview.' SPE Offshore South East Asia Conference, 6th, Preprints: 1986: 505-512.

THE BIKANER-NAGAUR BASIN

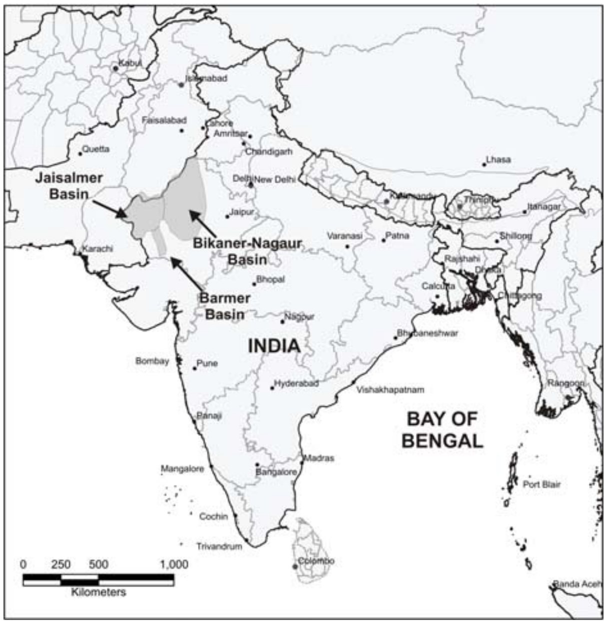


Figure A3. 10 Location of the Bikaner-Nagaur Basin

Introduction

The Bikaner-Nagaur Basin forms part of the Indus shelf. It lies in central Rajasthan, to the northeast of the Barmer Basin (Figure A3.10). It covers an area of 36,000 km^2.

Stratigraphy

The Bikaner-Nagaur Basin is essentially a Proterozoic to Lower Palaeozoic Basin overlain by a relatively thin succession of younger strata. In the deeper, western part of the basin, the succession typically comprises around 900 m of unfossiliferous sediments thought to be of Precambrian to Early Cambrian age and correlatable with the Marwar Supergroup, overlain by a thin sequence of Permo-Triassic strata and up to 600 m of Jurassic and younger rocks.

Hydrocarbons

Heavy crude oil has been discovered in multiple zones within the Proterozoic to Lower Palaeozoic sequence in all three deep wells drilled up to 1994 (Das Gupta & Bulgauda 1994). The main oil zones are: The Jodhpur Sandstone and the Bilara Dolostone, with further residual oil in the Hanseren Evaporite Formation (in two relatively thin siltstone layers) and the Upper Carbonate. Only the oil in the Jodhpur Sandstone is considered producible at the moment. It has an API gravity of 17°.

The principal cap rock is probably the Lower Palaeozoic salt beds in the Hanseren Evaporite Formation (Das Gupta & Bulgauda 1994).

CO_2 storage potential

Some CO_2 storage potential may exist in the Proterozoic reservoirs beneath the Hanseren Evaporite Formation, i.e. the Jodhpur Sandstone and the Bilara Dolostone. However, this cannot be quantified at present.

Reference

DAS GUPTA, U. & BULGAUDA, S.S. 1994. An overview of the Geology and Hydrocarbon Occurrences in the Western part of the Bikaner-Nagaur Basin. *Indian Journal of Petroleum Geology*, **3**(1), 1-17.

THE CAMBAY BASIN

Introduction

The Cambay Basin (Figure A3.11) is an intracratonic fault-bounded graben located near the western margin of the Indian craton (Biswas, 1987; Choudhary et al., 1997).

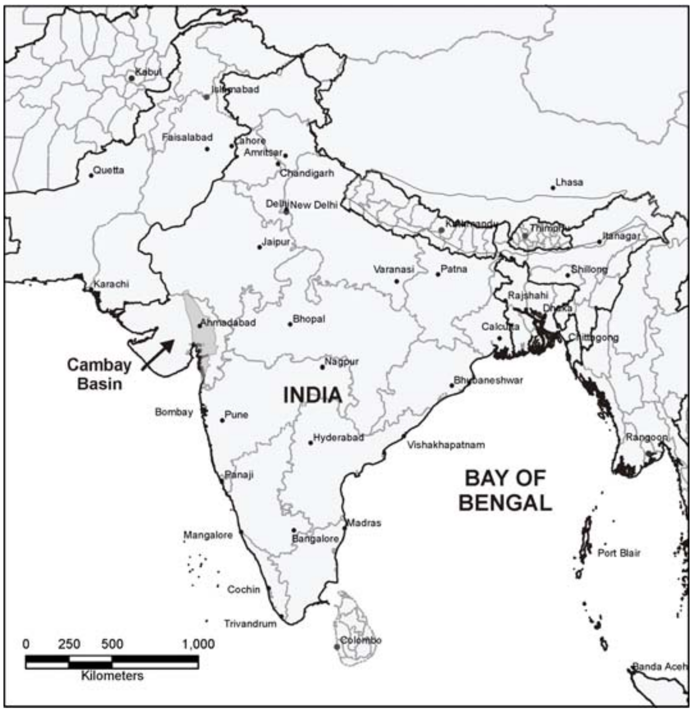


Figure A3. 11 Location map of Cambay Basin

The Basin is bounded by the Saurashtra peninsula to the west, the Mumbai Basin to the south, and by Precambrian rocks and the Deccan Traps to the east (Raju & Srinivasan, 1993). The northern end of Cambay Graben extends north of the Gujarat State boundary into Rajasthan, where it is known as the Barmer Basin. The Barmer Basin, where Cairn Energy have recently made some major oil discoveries, is described separately and not shown on Figure A3.11.

Structure

The Cambay Basin is a roughly NNW-SSE-trending elongate graben. It is generally subdivided into five tectonic blocks, based on recognised basement trends (Nanawati et al. 1995, Biswas et al., 1993, Figure A3.12).

The Basin was initiated at the end of the Cretaceous as a result of strike-slip movement along the Narmada-Son lineament (Roy, 1990).This formed a rift valley between the Saurashtra uplift and the Aravalli Range (Biswas, 1987)[2]. The main period of basin subsidence occurred during the early Cenozoic (Biswas, 1987). Cenozoic sedimentary rocks deposited on the Deccan Trap reach thicknesses of up to 11000 m (Dhar & Singh 1993).

---

[2] There is a Lower Cretaceous sedimentary sequence below the Deccan Trap but this likely predates basin development.

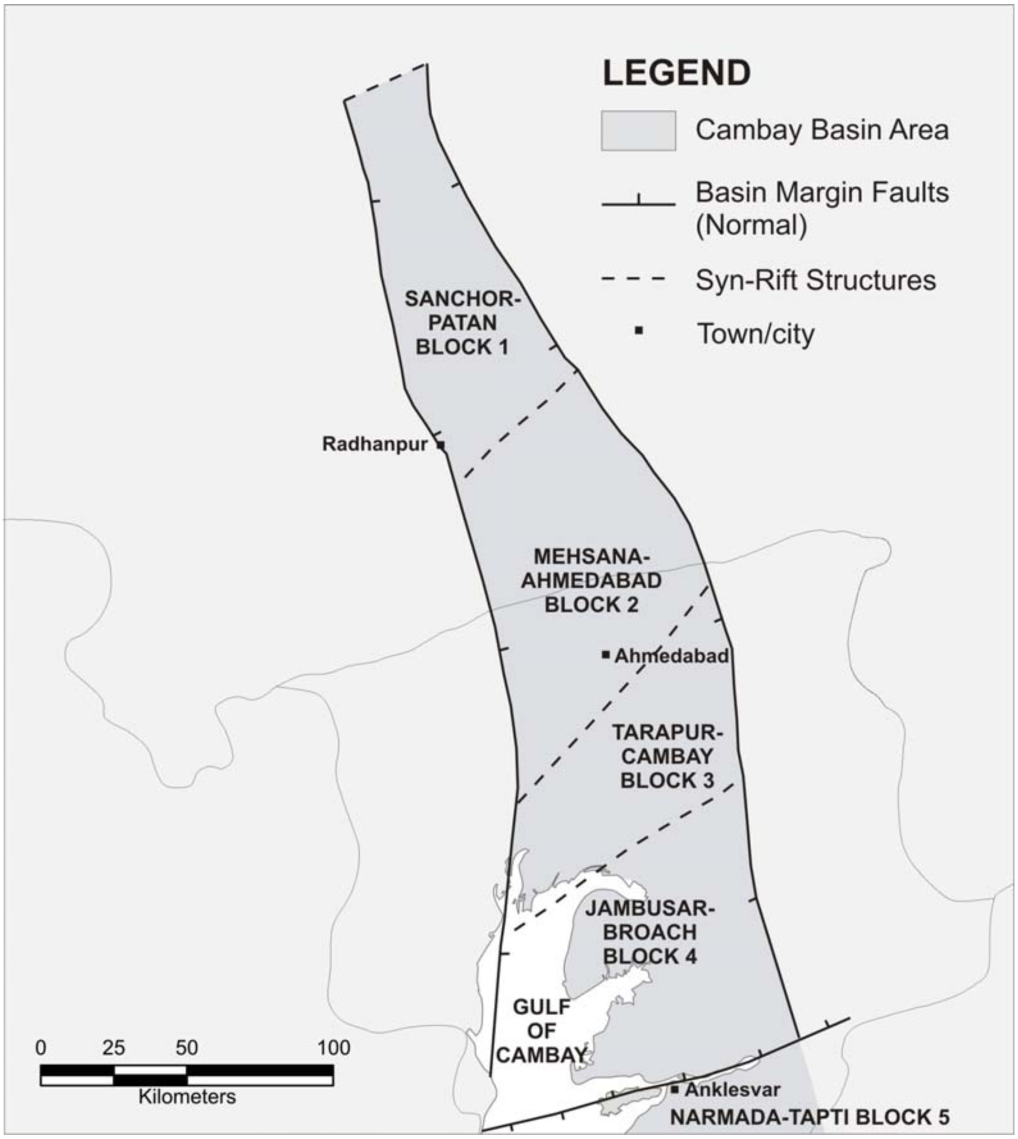


Figure A3. 12 Major structural blocks of the Cambay Basin

The depressions (the local name for areas of thicker basin fill) become progressively smaller and shallower northwards and, in the northern depressions, major faults are generally orientated parallel to the longitudinal axis of the Cambay graben. In the southern part of the graben, in the Jambusar block major faults are generally transverse and oriented across the Cambay basin (Dhar & Singh 1993).

Thick, synrift megasequences of Palaeocene-early Eocene age are present in the graben. These commonly thicken into listric and planar normal faults, which have tilted pre-rift strata. Many orthogonal transfer faults offset the major half-grabens. Episodic fault movement is indicated by at least three unconformities identified in the syn-rift sequences (Kundal et al., 1993).

A post-rift, thermal phase of subsidence took place during approximately Mid-Eocene to Mid-Miocene times. Later post-rift inversion (Middle Miocene and younger) shown by reverse movement along several listric normal faults, particularly in the Narmada-Tapti block, resulted in the formation of several anticlinal structures in the hanging wall sequences (Kundal et al., 1993, Roy, 1990).

Sanchor-Patan block

In the north of the Cambay Basin, in the Sanchor-Patan block, post-Deccan Trap sediments are up to 4 km thick in the Patan depression and up to 3.5 km thick in the broader Sanchor depression (Dhar & Bhattacharya 1993). The Wasna Horst is a prominent feature, it appears to have remained a positive feature until the end of the Middle Eocene and on it the Deccan Trap is encountered at a relatively shallow 1.1 km (Senapati et al., 1993).

Mehsana-Ahmedabad block

The north part of the Mehsana-Ahmedabad block is divided into eastern and western depressions either side of a N-S trending horst – the Mehsana horst. The south part of the block is dominated by the broad 7 km-deep Wavel depression (Dhar & Bhattacharya, 1993).

Tarapur-Cambay block

The northern margin of the Tarapur-Cambay block is delimited by the Nawagm shear, a NNE-SSW trending dextral transfer zone (Dhar & Bhattacharya, 1993). The Tarapur-Cambay block is a N-S trending structural depression that initiated as a half graben and became a full graben after deposition of the early synrift Olpad Formation (Dhar & Bhattacharya, 1993).

Jambusar-Broach block

The Jambusar-Broach block is dominated by the deep Broach depression that possibly contains up to 11 km of Cenozoic sedimentary rocks (Dhar & Bhattacharya 1993). It contains the greatest thickness of thermally mature Cambay Shale Formation –the region's most prolific source rock - and the largest oil field discovered to date in the south Cambay basin; the Gandhar oilfield (Biswas, et al. 1994). Based on deep seismic soundings, 1200 m of pre-Deccan Trap sedimentary rocks may be present beneath the Broach Depression (Kaila et al. 1979).

Narmada-Tapti block

The NE-SW trending Narmada shear zone defines the northern margin of the Narmada-Tapti block (Biswas, et al., 1994). Consequently, most structures in the Narmada block trend ENE-WSW (Dhar & Bhattacharya, 1993). This block also contains some large oil and gas fields, e.g. the Ankleshwar field.

Stratigraphy

The stratigraphy of the Cambay Basin is summarised in Figure A3.13. The Basin is underlain by Precambrian igneous and metamorphic basement, which is exposed along its eastern margin (Mukherjee 1983).

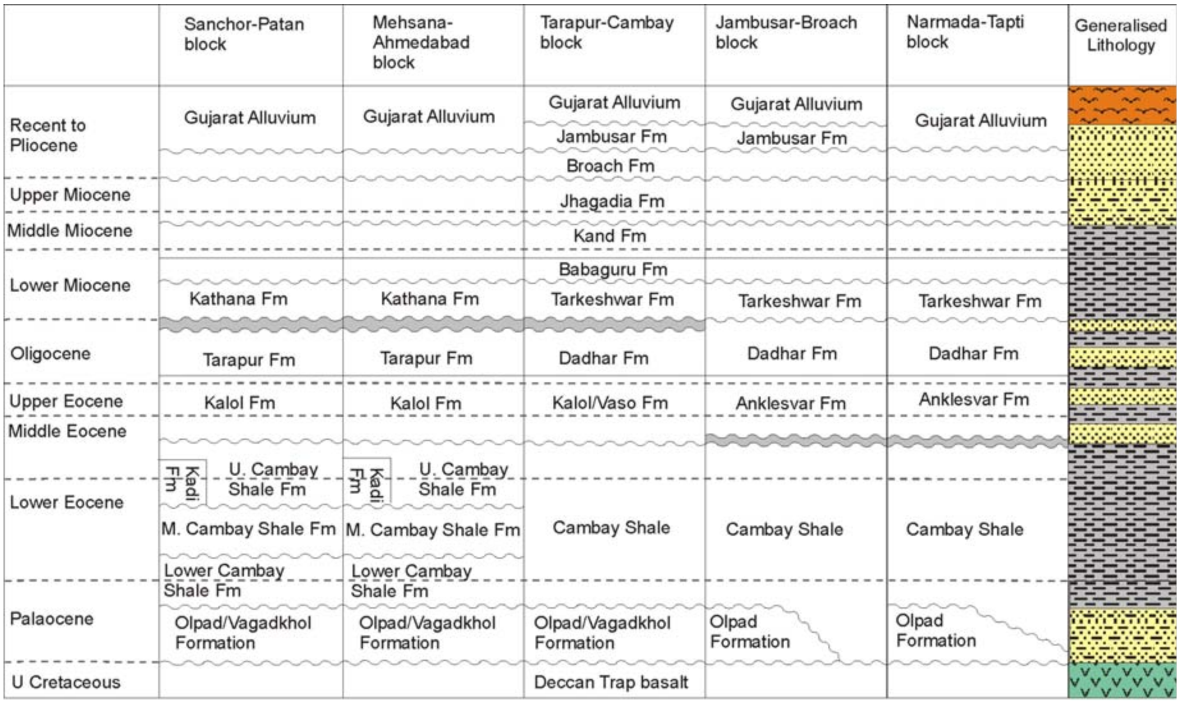


Figure A3.13 Summary stratigraphy of the Cambay Basin (adapted from Raju & Srinivasan 1993 and Wani et al. 1995)

Pre-Deccan Trap sedimentary rocks

A Lower Cretaceous sedimentary sequence is exposed on the margins of the Cambay Basin, in the northeast of the Saurashtra peninsula, on the western and part of the eastern margins of the Cambay Basin, as inliers in the Narmada Valley, and to the north of the Cambay Basin in the Barmer area (Mukherjee, 1983). Similar Lower Cretaceous arenaceous fluvial deposits resting on granitic basement have been encountered in wells in the Cambay Basin (Dhar & Singh, 1993 and Senapati et al 1993). Upper Cretaceous sediments were either not deposited or were eroded before the Deccan basalt volcanism (Dhar & Singh, 1993).

Deccan Traps

At the end of the Cretaceous, very extensive subaerial volcanic activity (eruption of the Deccan Traps) occurred in the Cambay, Saurashtra and Kutch basins (Biswas, & Deshpande 1973). The Deccan Trap volcanics are several hundred metres thick on the east and west flanks of the south Cambay Basin (Biswas, et al., 1994). In the Anklesvar deep well, over 3200 m of basalt was penetrated, without encountering its base (Biswas et al. 1994).

Palaeocene- Early Eocene

During the Palaeocene, a sedimentary sequence consisting of several hundred metres of weathering products from the Deccan volcanics (the Olpad Formation) was laid down during the initial stages of rifting, in stacked and overlapping alluvial fans along fault scarps (Biswas, et al., 1994; Biswas, 1987; Raju & Srinivasan, 1993). Surprisingly, this Formation appears to have some petroleum source potential (see below).

The Olpad Formation is unconformably overlain by a fossiliferous petroleum source rock; the late Palaeocene-early Eocene Cambay Shale, which was deposited during the first major marine transgression of the basin (Biswas et al. 1994, Biswas 1987). The Cambay Shale is dark, rich in organic matter and often carbonaceous (Biswas et al. 1994).

The early Eocene transgression that resulted in deposition of the Cambay Shale encroached as far northwards as the northern part of the Mehsana-Ahmedabad block (Raju & Srinivasan, 1993).

Early Middle Eocene to Late Eocene

Above the Cambay Shale, three Eocene transgressive cycles are recognised; early Middle Eocene, Middle Eocene and Late Eocene, deposition in slow regressive cycles occurring in the intervening periods (Raju & Hardas, 1985, Raju & Srinivasan, 1983). In the north Cambay Basin, the regressive cycles were deposited in deltaic-backshore-lagoonal-fluvial environments, whereas in the south Cambay basin a marine deltaic environment prevailed with a tidal gulf separating the two halves of the basin on the Tarapur block (Raju & Hardas, 1985).

Two significant drainage systems developed during Middle Eocene times, depositing the Kalol Formation on the Ahmedabad-Mehsana block and the Anklesvar Formation on the Jambusar-Broach and Narmada-Tapti blocks. The Cambay-Tarapur block (in the centre of the basin) was starved of coarser clastic material and so has poor Middle Eocene reservoir potential (Raju & Srinivasan, 1993).

In the north part of the Cambay Basin, the silty Kadi Formation (potential reservoir rock) overlies the Cambay Shale (potential source rock) and the Kalol Formation (potential reservoir rock) deposited during the Eocene in a fluvial channel to tidal environment (Wani et al., 1995). The Kadi and Kalol formations are difficult to distinguish in the Patan area and so are commonly grouped together and known as the Tharad Formation (Raju & Srinivasan, 1993).

In the south part of the Cambay Basin, the Cambay Shale is overlain by the deltaic Anklesvar Formation. This includes the Hazad Member (important reservoir sandstone), Kanwana Shale, Ardol Member (deltaic sandstone) and Telwa Shale Member (an effective seal).

Late Eocene to Early Miocene

The shaly Tarapur Formation (and its equivalent in the south Cambay basin, the Dadhar Formation) represents a regional cap-rock and was deposited across the whole Cambay Basin in the Latest Eocene to Oligocene (Raju & Srinivasan, 1993).

A further widespread marine transgression in the Upper Oligocene-Lower Miocene resulted in the deposition of the Kathana Formation in the northern part of the basin and the Tarkesvar Formation in the southern part of the basin (Raju, 1968; Biswas, 1994; Wani et al., 1995,)

Miocene to Neogene

There is an unconformity between the Kathan and Tarkesvar Formations and the overlying Early Miocene Babaguru Formation. A further unconformity occurs between the Babaguru Formation and the overlying Kand Formation (Wani et al., 1995; Raju & Srinivasan, 1993). The Jhagadia Formation was deposited unconformably on the Kand during the middle-late Miocene (Wani et al., 1995). During the later Neogene, the Cambay Basin subsided only slowly and the coast retreated further south to its present position (Raju & Srinivasan, 1993).

Hydrocarbons

There are several producing fields in the Cambay Basin. Some 4000 wells have been drilled over 40 years. These have yielded some 2.1 billion barrels of reserves and over 1 Tcf of gas.

In summary:

- The Cambay Shale (and possibly the Olpad Formation) are the main source rocks.
- 90% of the confirmed oil and gas reserves are in Middle Eocene reservoir rocks.
- Reactivation of faults during the early Miocene resulted in the formation of anticlinal structures which later trapped migrating hydrocarbons in fields such as Anklesvar, Kosamba, Motwan, Olpad, Jhagadia and Hazira (Roy 1990).
- Strong southward tilt of the Broach depression due to subsidence along the Narmada Fault resulted in development of fault-controlled anticlinal features such as the plunging anticline at Gandhar, the closures at Dabka and Daheja and other features (Roy, 1990).
- About 56% of the discovered hydrocarbons occur in structural traps and 44% in stratigraphic and combination traps (Dhar & Bhattacharya, 1993).
- The (Oligocene) Tarapur Shale Formation forms a regional cap rock (Raju & Srinivasan, 1993).

The location of the main fields in the Cambay basin is shown in Figure A3.14.

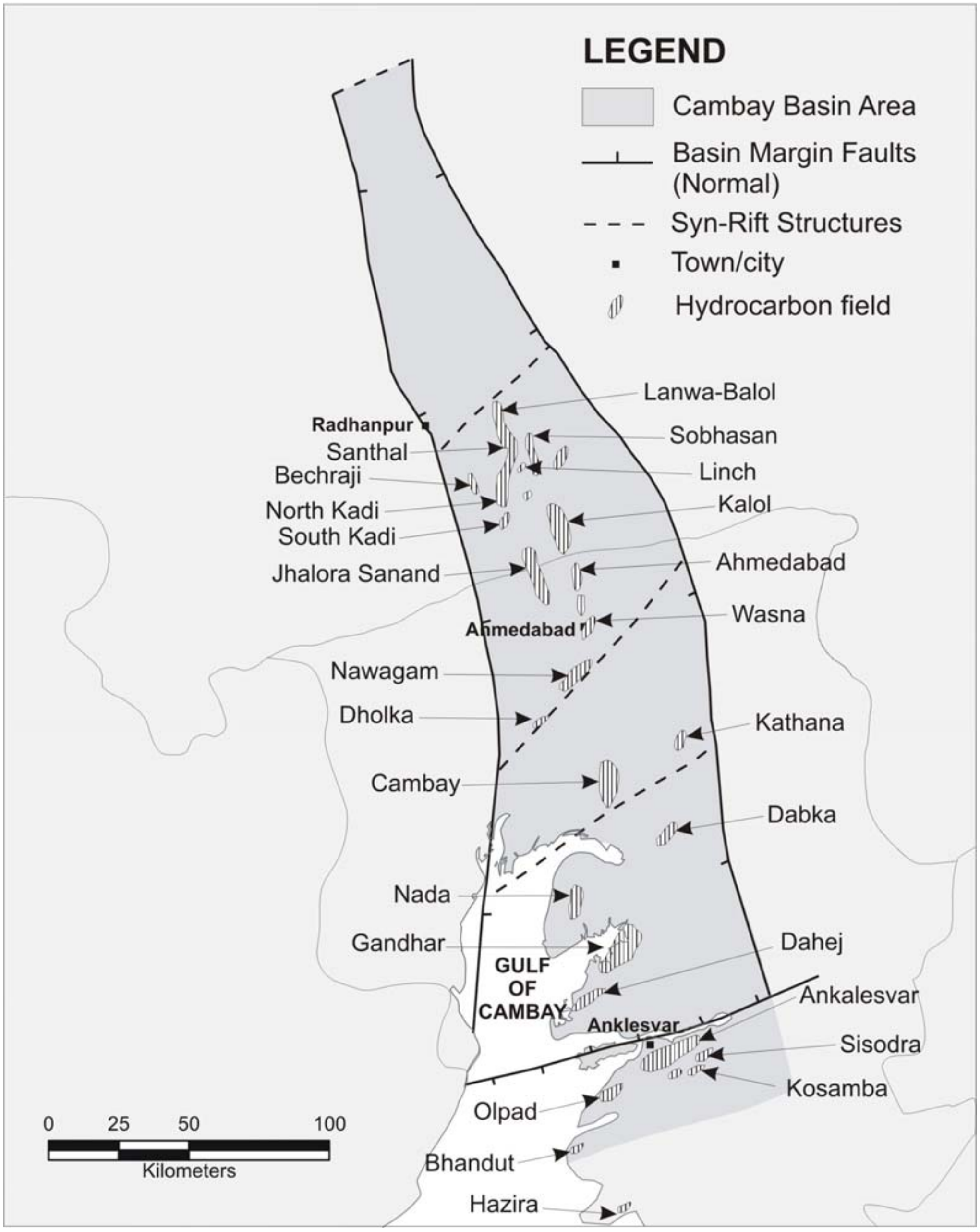


Figure A3.14 Location of the main oil and gas fields in the Cambay Basin (adapted from Raju and Srinivasan 1993, Roy 1990, Dhar & Bhattacharya 1993)

CO_2 storage potential

There is good CO_2 storage potential in the Cambay Basin.

The main petroleum reservoir rocks, and thus proven sealed reservoirs, are of Middle-Upper Eocene age. Porosity is frequently in the range 2-14% (Hardas et al. 1989, Senapati et al. 1993) and permeability is in the range 0.3-162.5 mD (Senapati et al. 1993, Mandal & Bhattacharya 1997). The Tarapur Shale Formation forms a regional cap rock above these reservoirs (Raju & Srinivasan, 1993).

In the central Cambay Basin, the top of the Middle-Upper Eocene Kalol Formation reservoir is at 880 m -790 m and forms a domal structure (Dhar & Bhattacharya 1993), which may be suitable for CO_2 storage. The Anklesvar Formation in the south Cambay Basin is at depths of 750 m to 3100 m, and contains smaller domal structures that may be suitable for CO_2 storage (Biswas et al. 1994).

In parts of the Gulf of Cambay, hydrocarbons have been trapped in domal structures capped by the overlying Miocene Kand Shale (Biswas et al., 1994).

The present day geothermal gradient in the Cambay basin is 29.8-35.0ºC/km (Singh et al., 1995).

References

Biswas, S. K. 1987. Regional tectonic framework, structure and evolution of the western marginal basins of India. *Tectonophysics,* **135**, 307-327.

Biswas, S. K. 1987. Regional tectonic framework, structure and evolution of the western marginal basins of India. *Tectonophysics,* **135**, 307-327.

Biswas, S.K., Bhasin, A.L. & Ram, J. 1993. Classification of Indian Sedimentary Basins in the Framework of Plate Tectonics. *Proceedings of the second seminar on Petroliferous basins of India*, **Vol. 1**, 1-46.

Choudhary, R.N., Bondre, S.A. & Sharma, B.K. 1997. Resistivity-TOC ratio as an indicator of maturity level for oil generation – Cambay basin, India. *Proceedings Second International Petroleum Conference and Exhibition PETROTECH-97, New Delhi,* pp213-221.

Dhar, P.C. & Bhattacharya, S.K. 1993. Status of exploration in the Cambay basin. In: Biswas, S.K., Dave, A, Garg, P., Pandey, J, Maithani, A., Thomas, N. J. (eds.), *Proceedings Second Seminar on Petroliferous basins of India*, **Vol. 2**, Indian Petroleum Publishers, Dehra Dun, India, pp1-32.

Dhar, P.C. & Singh, R.P. 1993. Evolution of Cambay graben. Rifted Basins and aulacogens: Geological and geophysical Approach 1993. Casshyap et al (eds). Pp268-280

Kaila, K.L., Tiwari, H.C. & Tripathi, K.M. 1979. Deep sounding seismic sounding studies along Navibander-Amreli profile. Saurashtra, Gujarat, India. *Technical Report National Geophysics Research Laboratory*, Hyderabad.

Kundal, J., Wani, M.R., Thakur, R.K. 1993. Structural style in South Cambay Rift and its control on postrift deltaic sedimentation. In: Biswas, S.K., Dave, A, Garg, P., Mandal, A.K. & Bhattacharya, V.K. 1997. Revival of oil production from Linch field of Cambay Basin by solvent stimulation technique. *Proceedings Second International Petroleum Conference and Exhibition PETROTECH-97, New Delhi*, pp270-284.

Mishra, K.S. 1981. The tectonic setting of Deccan volcanics in southern Saurashtra and northern Gujarat. In: Subbarao, K.V. & Sukheshwala, R.N. (eds), *Deccan Volcanism*, Geological Society India, Bangalore, pp81-86.

Mukherjee, B.K. & Kapoor, P.N. 1995. 'Organic Matter Maturation Studies of Tertiary Sequences in Shelf Area of Bengal Basin, India.' *Proceedings of PETROTECH-95, New Delhi Technology Trends in Petroleum Industry,* pp373-384.

Nanawati, V., Jain, A.K., Singh, H. & Shukla, R.K. 1995. Efficacy of Olpad formation as source rock in Ahmedabad-Mehsana block of Cambay basin, India. *Proceedings PETROTECH-95, Technology Trends in Petroleum Industry*, pp245-253.

Pandey, J, Maithani, A., Thomas, N. J. (editors), *Proceedings Second Seminar on Petroliferous basins of India*, **Vol 2**, Indian petroleum publishers, Dehra Dun 248001, India, pp79-96

Raju, A.T.R. & Hardas, M.G. 1985 Middle Eocene environments in Cambay basin. *Petroleum Asia Journal*, **8**(11), 86-106.

Raju, A.T.R. & Srinivasan, S. 1983. More hydrocarbons from well explored Cambay basin. In: L L Bhandari, B S Venatachala, R Kumar, S N Swamy, P Garga and D C Srinastava (editors), *Petroliferous basins of India.* Petroleum Asia Journal, **6**(4), 25-35.

Raju, A.T.R. & Srinivasan, S. 1993. Cambay basin - petroleum habitat. In: Biswas, S.K., Dave, A, Garg, P., Pandey, J, Maithani, A., Thomas, N. J. (editors), *Proceedings of the second seminar on Petroliferous basins of India*, **Vol 2**, India petroleum publishers, Dehra Dun, India, pp33-78.

Roy, T.K. 1990. Structural styles in southern Cambay basin India and role of Narmada Geofracture in formation of giant hydrocarbon accumulations. *Bulletin ONGC,* **27**(1), pp15-56.

Senapati, R.B., Singh, N.K., Kumar, A. & Tikku, C.L. 1993. Hydrocarbon prospects of Patan Area, Patan-Sanchor block, north Cambay Basin, India. *Bulletin of the Oil and Natural Gas Corporation Limited*, 30(2), 59-81.

Wani, M.R. & Kundu, J. 1995. Tectonostratigraphic analysis on Cambay Rift basin India: Leads for future exploration. *Proceedings PETROTECH-95, Technology Trends in Petroleum Industry,* pp147-164.

The Cauvery Basin

Introduction

The Cauvery Basin (Figure A3.15) is located at the southern end of the east coast of India and lies in the state of Tamil Nadu, south of Chennai (formerly Madras). The Indian part of the basin covers an area of 25,000 km^2 onshore and around 35,000 km^2 offshore. The offshore part of the basin lies between India and Sri Lanka. The western limits of the basin are formed by exposures of Archaean rocks (which have no CO_2 storage potential).

Figure A3. 15 Location of the Cauvery Basin

Structure

Development of the Cauvery Basin resulted from extension between India and Sri Lanka during the break-up of Eastern Gondwanaland (Narasimha Chari et al. 1995) in early Cretaceous times. It is a NE-SW trending pericratonic rift basin containing sedimentary rocks of Early Cretaceous to Recent age.

NE-SW-trending fault movement controlled Early Cretaceous sedimentation and resulted in the development of a series of horsts graben and half-graben. A map of these structural elements is given in Narasimha Chari et al. (1995). In early Cenozoic times the basin was tilted down to the ESE and the blocks and basins were subjected to a series of transgressive-regressive events (Kumaraguru et al. 2005). Consequently the basin fill contains major unconformities and has low regional dips trending towards the ESE.

The various structural elements of the Cauvery Basin are briefly described below:

Pondicherry Sub-basin

Located in the northern part of the Cauvery Basin, this is a linear feature that extends from onshore to offshore. It is bordered by Archean granites and gneisses to the west and by the subsurface Kumbhakonam-Shiyali Ridge to the southeast. Thick lignite beds occur in this depression. They are exploited in the Neyveli Lignite Field.

Kumbhakonam-Shiyali Ridge

A subsurface basement ridge consisting of Precambrian basement overlain by approximately 1.8 km of sedimentary rocks, most of which are of Cenozoic age.

Madanam Ridge

A large dome-shaped feature lying offshore to the north of Madanam, it is offset from the Kumbhakonam-Shiyali Ridge. Cenozoic sediments 1.6-2 km in thickness lie unconformably on basement rocks here.

Thanjavur Sub-basin

This depression is bounded by the Precambrian crystalline shield to the WNW and the Devakottai-Mannargudi Ridge to the ESE. The maximum depth to basement is 3-4 km and the depression gradually shallows towards its margins. The Cenozoic is very thin here.

Tranquebar Sub-basin

The maximum depth of this depression is approximately 4.5 km. It lies partly on- and partly offshore; there is about 2.5 km of Cenozoic sedimentary cover.

Karaikal Ridge

A linear feature, which lies on- and offshore. Depths to basement are in the order of 1 km in the northeast and 2.5 km in the southwest. Cretaceous sediments are absent over large parts of this feature and all the cover is Cenozoic.

Nagapattinum Sub-basin

This depression extends into the Bay of Bengal. Depths to basement reach 4.5 km.

Vedarniyam High

This high is located mostly offshore and connects with the northern tip of Sri Lanka. It contains about 1.5 km of Cenozoic sediments

Devakottai-Mannargudi Ridge

A long ridge extending along the NW margin of Palk Bay that separates the Thanjavur and Ramnad-Palk Bay sub-basins. Depth to basement increases slowly to the northeast, where it is at almost 1 km. There are mainly Cenozoic sediments overlying this ridge.

Palk Bay Sub-basin

This depression lies mainly offshore and contains approximately 4.5 km of sedimentary rocks, nearly half of which are Cenozoic in age. It is petroleum-bearing.

Mannar Sub-basin

This is an offshore feature lying in the Gulf of Mannar. Here Cretaceous rocks overlie the basement.

5.4.1 Stratigraphy

Sedimentary rocks filling the basin range in age from Early Cretaceous to Recent, and are up to 6 km thick. A thick sequence of Cretaceous strata and a moderately thick section of Cenozoic strata overlie the Archean basement. A thin layer of alluvium covers most of the Cenozoic sediments (Mukhopadhyay et al., 2005). The stratigraphy of the onshore Cauvery Basin has recently been revised by Watkinson et al. (2007).

Reservoir rocks and seals

The best reservoir potential for CO_2 storage lies in Cretaceous sandstone reservoirs. In general, sandstone reservoirs in the Upper Cretaceous are good quality with intergranular and interconnected dissolution pores, whereas sandstone reservoirs in the Lower Cretaceous are low quality with mainly micropores and few interconnected pores (Lahiri et al., 1997).

The (sealed) hydrocarbon-bearing formations are the Lower Andimadam, Upper Andimadam and Bhuvanagiri/Upper Palk Bay formations – all form part of the Uttatur Group - and the Nannilam Formation, which belongs to the Trichinopoly and Ariyalur Groups (Govindan et al. 2000).

Lowstand fans and wedges may also form good reservoirs (Watkinson et al. 2007, Prabhakar et al. 1993).

Existing oil and gas traps are mainly of combination stratigraphic and structural types.

CO_2 Storage Potential

The presence of oil and gas fields in the Cauvery Basin indicates that the potential to store CO_2 in this area is high. This is particularly so in Mid- to Upper Cretaceous sequences where reservoir quality is good and there are interbedded seals.

References

Govindan, A., Ananthanarayanan, S. & Vijayalakshmi, K.G. 2000. Cretaceous petroleum system in Cauvery Basin, India. In: Govindan, A. (editor), *Franz Kossmat volume; Cretaceous stratigraphy, an update*. Memoir Geological Society of India, **46**, 365-382.

Kumar, S.P. 1983. Geology and Hydrocarbon Prospects of Krishna Godavari and Cauvery Basins. In: L.L. Bhandari, B.S. Venatachala, R. Kumar, S.N. Swamy, P. Garga & D.C. Srinastava (editors), *Petroliferous Basins of India*. Petroleum Asia Journal, **6**(4) November 1983, pp 57-65.

Lahiri, G. & Hardas, M.G. 1997. Diagenetic effects on sandstone reservoirs of Nannilam Field, Cauvery Basin. *Journal Geological Society of India*. **49(**6), 61-674.

Mukhopadhyay, S.K., Kumaraguru, P, Bandopadhyay, Shyamali. 2005. Depositional model for lignite deposits in Cauvery sedimentary basin, Tamil Nadu. *Special Publication Series - Geological Survey of India*, **81**, 62-100.

Narasimha Chari, M.V., Sahu, J.N., Banerjee, B., Zutshi, P.L. & Kuldeep Chandra. 1995. Evolution of the Cauvery basin, India from subsidence modelling. *Marine and Petroleum Geology*, **12**(6) 667-675.

Prabhakar, K.N., Awasthi, A.K., Roy, S.K., Prakesh, A., Gupta, R. & Kumar, I.J. 1993. Sequence Stratigraphy and Systems Tract Analysis of Nagapattinam Subbasin Cauvery Basin. In: Biswas, S.K., Dave, A, Garg, P., Pandey, J, Maithani, A., Thomas, N. J. (editors), *Proceedings of the second seminar on Petroliferous basins of India*, **Vol. 1**, pp203-215.

Ramkumar, M., Stueben, D., & Berner, Z. 2003. Lithostratigraphy, depositional history and sea level changes of the Cauvery Basin, southern India. *Geoloshki Anali Balkanskoga Poluostrva*, **65**; Pages 1-27. Zavod za Regionalnu Geologiju i Paleontologiju, Belgrade, Yugoslavia.

Ramkumar, M., Subramanian, V. & Stueben, D. 2005. Deltaic sedimentation during Cretaceous period in the northern Cauvery Basin, South India; facies architecture, depositional history and sequence stratigraphy. *Journal of the Geological Society of India*, **66**(1), 81-94.

Thomas, N.J., & Sharma, V.N. 1993. Thermal Evolution of Source Rocks in Cauvery Basin. In: Biswas, S.K., Dave, A, Garg, P., Pandey, J, Maithani, A., Thomas, N. J. (editors), *Proceedings of the second seminar on Petroliferous basins of India*, **Vol. 1**, 245-254.

Watkinson, M.P., Hart, M.B. & Joshi, A. 2007. Cretaceous tectonostratigraphy and the development of the Cauvery basin, southeast India. *Petroleum Geoscience*, **13**, 181-191.

THE CHHATTISGARH BASIN

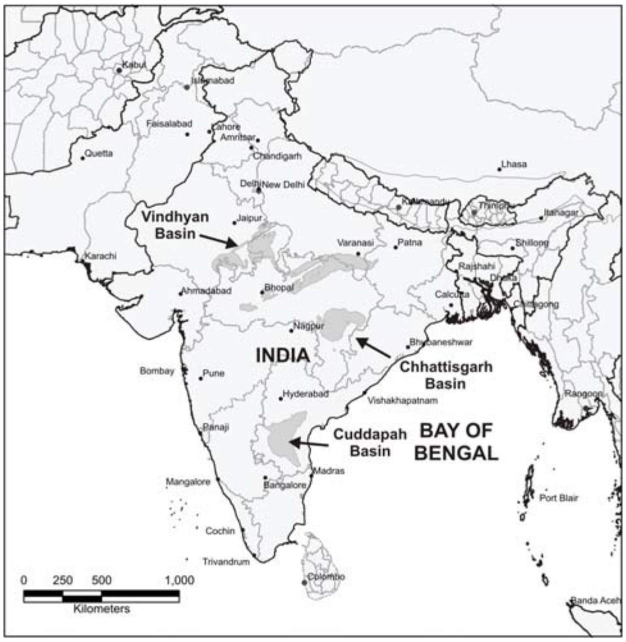


Figure A3. 16 Location of the Chhattisgarh Basin

Introduction

The Chhattisgarh Basin is an intracratonic Proterozoic sedimentary basin in central India (Figure A3.16). The Proterozoic sedimentary rocks rest unconformably on the Archaean basement complex of the Indian shield. It has not been extensively studied and its depth, tectonics and structural features are poorly known.

5.4.1.1 STRUCTURE

Gravity data suggest that the Chhattisgarh Basin reaches a maximum depth of around 3.5 km (Singh et al. 1990).

5.4.1.2 STRATIGRAPHY

The basin fill (Figure A3.17) comprises a thick succession of sandstone, shale and limestone known as the Chhatisgarh Supergroup (Naqvi & Rogers 1987, Murti 1987, 1996, Das et al. 1992, Datta 1998, Das et al. 2001, Gupta 1998, Datta et al. 1999, Patranabis Deb & Chaudhuri 2002).

The lower part of the succession (the Chandarpur Group) is dominated by sandstone and consists of purple sandstone and buff shales. The upper part (the Raipur Group) is dominated by limestone and shale.

The Chandarpur Group comprises undeformed, unmetamorphosed and gently dipping to subhorizontal strata and is further subdivided into three formations (Figure A3.19).

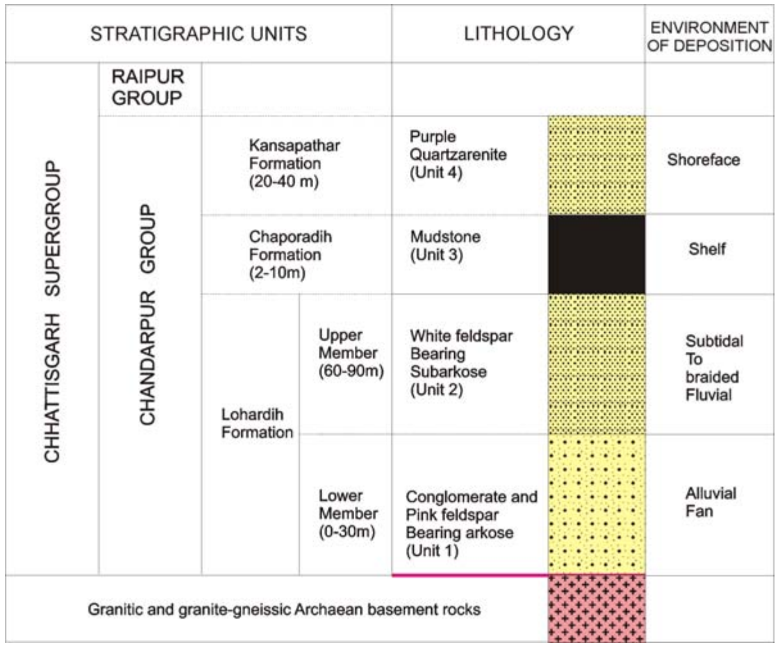


Figure A3. 17 Stratigraphy of the Chhattisgargh Supergroup

The lowest sequence, known as the Lobardih Formation, comprises up to 120 m of conglomeritic sandstones deposited in alluvial fans and braided river to subtidal environments (Datta et al. 1999).

The overlying Chaporadih Formation (2–10 m) is dominated by thinly laminated mudstone. Towards the top, heterolithic facies composed of coarse-grained ripple beds and mudstone appear. It is believed to represent the deposits of a quiet water shelf occasionally perturbed by storm waves.

The Kansapathar Formation (20–40 m), the topmost unit of the siliciclastic Chandarpur Group, is made up of medium-grained, well sorted, purple coloured quartzarenite, glauconitic in places. It is an extensive sheet-like sand body with a gradational to sharp contact with the underlying unit. It records a fluvial to marine transition (Datta et al. 1999). In general, the individual sandstone beds are 30 cm to 1.5 m thick, are commonly cross-stratified, slightly wavy and sheet-like, but in places show pronounced lenticular geometry.

K–Ar dating of authigenic glauconite from the lower part of the Chhattisgarh Supergroup indicates an age of 700–750 Ma (Kreuzer et al., 1977).

There is no published detailed pertrographic work on the Chhattisgarh Supergroup.

Carbon dioxide storage potential

The CO_2 storage potential of this basin cannot be assessed properly on the basis of currently available information. Although it is premature to write it off completely, its Proterozoic age suggests that it is unlikely to contain well sealed, highly porous and permeable reservoir rocks at depth. Therefore its CO_2 storage potential is presently classified as limited.

References

Das, D.P., Kundu, A., Das, N., Dutta, D.R., Kumaran, K., Ramamurthy, S., Thanavelu, C. and Rajaiya, V. 1992 Lithostratigraphy and sedimentation of Chattisgarh Basin; *Indian Minerals* **46**, 271–288.

Das, N., Dutta, D.R. and Das, D.P. 2001. Proterozoic cover sediments of southeastern Chattisgarh state and adjoining part of Orissa. *Geological Survey of India Special Publication* **55**, 237–262.

Datta, B. 1998. Stratigraphic and sedimentologic evolution of the Proterozoic siliciclastics in the southern part of Chattisgarh and Khariar, central India; *Journal of the Geological Survey of India,* **51**, 345–360.

Datta, B., Sarkar, S. and Chaudhuri, A.K. 1999. Swaley crossstratification in medium to coarse sandstone produced by oscillatory and combined flows: examples from the Proterozoic Kansapathar Formation, Chattisgarh Basin, M.P., India; *Sedimentary Geology* **129**, 51–70.

Gupta, A. 1998. Hummocky cross-stratification in the Chattisgarh Basin, M.P. and its hydraulic and bathymetric implications. *Journal of the Indian Association of Sedimentologists* **17**(2), 213–224.

Kreuzer, H., Karre, W., Kursten, M., Schnitzer, W.A., Murti, K.S. and Srivastava, N.K. 1977. K/Ar dates of two glauconites from the Chandarpur-Series (Chattisgarh/India): on the stratigraphic status of the late Precambrian basins in central India. *Geol. Jb*. **B28**, 23–36.

Moitra, A.K. 1995. Depositional environmental history of Chattisgarh Basin, M.P., based on stromatolites and microbiota. *Journal of the Geological Society of India* **46**(4), 359–368.

Murti, K. S. 1987. Stratigraphy and sedimentation in Chattisgarh Basin; In: *Purana basins of peninsular India,* Memoir of the Geological Society of India **6**, 239–260.

Murti, K.S. 1996. Geology, sedimentation and economic mineral potential of the south-central part of Chattisgarh Basin. *Geological Survey of India Memoir* **125**, 139.

Naqvi, S.M. and Rogers, J.J.W. 1987. *Precambrian Geology of India*, Oxford University Press, New York, U.S.A., 223pp.

Patranabis Deb, S. and Chaudhuri, A.K. 2002. Stratigraphic architecture of the Proterozoic succession in the eastern Chattisgarth Basin, India: tectonic implications, *Sedimentary Geology* **147,** 105–125.

Singh, V.P., Shanker, D. & Singh, R. 1990. *A structural and tectonic synthesis of parts of Archeans, Satpuras and Chhattisgarh basins around Mandalaraipur districts, M.P., India, using gravity field data.* Dept. of Science and Technology (DST), New Delhi, Project No. ES/23/119/90, 16pp.

THE CUDDAPAH BASIN

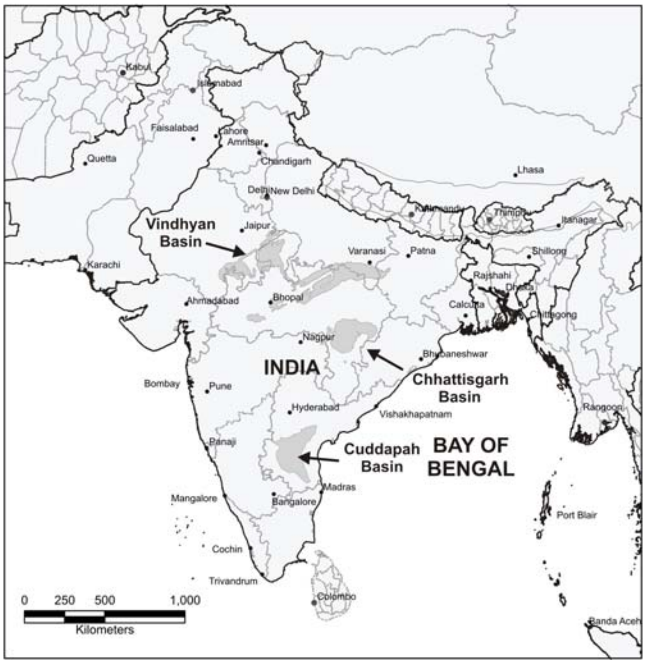


Figure A3.18 Location of the Cuddapah Basin

Introduction

The crescent-shaped Cuddapah Basin is a Proterozoic intracratonic sedimentary basin on the eastern margin of the Eastern Dharwar Craton (Figure A3.18). It rests unconformably on Archaean gneiss and granite basement rocks.

Covering an area of about 34,000 km^2, the basin contains sedimentary and igneous rocks that dip gently to the east, on average at about 10-15°. It is one of the better studied Proterozoic basins of India (e.g. Rao & Murthy, 1978; Mishra, 1992; Verma & Dutta, 1994; Prasanti Lakshmi & Ram Babu, 2002).

Structure

Based upon aeromagnetic data, the basin may reach a maximum thickness of around 10 km near Muddanuru (Prasanti Lakshmi & Ram Babu, 2002).

Stratigraphy

The Cuddapah Basin contains Proterozoic, predominantly sedimentary rocks which are divided into the Cuddapah and Kurnool supergroups. In places, the sedimentary rocks are interlayered with sills, tuffs and lava flows.

The Cuddapah Supergroup is of middle Proterozoic age (1600–1300 Ma). It is dominantly argillaceous and arenaceous, with subordinate calcareous strata and is divided into three groups, the Papagni, Chitravati and Nallamalai Groups. Rocks of the Nallamalai Group crop out in the eastern part of the basin and are highly disturbed, folded and faulted.

The overlying Kurnool Supergroup, of middle to late Proterozoic age (980–520 Ma), is found in the central part of the basin. It is divided into three subgroups, each of which starts with a quartzite and ends with a shale unit. It is thought to have been deposited in a shallow marine shelf environment.

Igneous rocks

A large lopolithic intrusion, manifested by a positive gravity anomaly, occurs in the south-western part of the basin. Concentric sills following the arcuate western and south-western margins of the basin occur around the lopolithic intrusion. Mafic sills and dykes occur in and around the basin margins (contemporary dykes occur in the Napier complex of East Antarctica). Dykes and dyke swarms tend to trend in NW-SE and NE-SW directions. The igneous rocks in and around Cuddapah basin vary in age between 650 Ma and 1850 Ma with episodic emplacements and a peak period of activity between 1400 and 1200 Ma.

Carbon dioxide storage potential

The CO_2 storage potential of this basin cannot be assessed properly, not least because there is no information available on the porosity and permeability of its potential reservoir rocks. Although it is premature to write it off on the basis of the information outlined above, its great age suggests that it is unlikely to contain well sealed highly porous and permeable reservoir rocks at depth. Therefore its CO_2 storage potential is presently classified as limited.

References

Mishra, D.C., 1992. Mid-continental high of Central India and the Gondwana tectonics. *Tectonophysics,* **212**, 153-161.

Prasanti Lakshmi, M. & Ram Babu, H.V. 2002. Basement structure of the southwestern part of the Cuddapah Basin from aeromagnetic anomalies. *Current Science*, **82**(11), 1378-1381.

Rao, B.S.R. & Murthy, I.V.R., 1978. *Gravity and magnetic method of prospecting*, Arnold Heineman publisher (India) Pvt. Ltd., New Delhi, 390-395.

Verma, R. K. and Dutta, U., 1994. Analysis of aeromagnetic anomalies over the central part of the Narmada-Son-Lineament. *Pure Applied Geophysics*, **142**, 383-405.

THE DAMODAR VALLEY BASINS

The Damodar Valley lies in the north-eastern part of peninsula India, in the States of Jarkhand and West Bengal. It contains a number of important Gondwana coal-bearing basins.

Structure

The Damodar Valley basins are found within the ENE-WSW-trending Permian to Mesozoic Narmada-Son-Damodar Graben. The graben follows the Satpura Precambrian structural trend, and transects the middle of the Indian shield, forming a major mid-continental rift. It overlies a transtensional pull-apart basin on the same trend that was initiated during Proterozoic times (Biswas 1992). The basins are coal-bearing and the described in detail in Appendix 2.

Stratigraphy

Generally, the Lower Permian sediments of the Damudar Group were deposited unconformably on the Pre-Cambrian basement (Figure A3.19). However, pre-Permian Upper Palaeozoic sediments are present in a few places (Dutta 2002).

AGE	LITHOLOGY	FORMATION /GROUP		DEPOSTIONAL ENVIRONMENT	THICKNESS RANGE (M)
LOWER JURASSIC	CONGLOMERATES, SANDSTONES AND SILTSTONES. MINOR CLAY BANDS	MAHADEVA (OR SUPRA-PANCHET) FORMATION		BRAIDED RIVER SYSTEM	LESS THAN 800
TRIASSIC	ALTERNATING SHALE AND SANDSTONE	PANCHET FORMATION		MEANDERING RIVER SYSTEM	1000
UPPER PERMIAN	SANDSTONE, SHALE, SILTSTONE, COAL SEAMS	DAMUDA GROUP	RANIGANJ FORMATION	MEANDERING RIVER SYSTEM	900
LOWER PERMIAN	SANDSTONE, SHALE, SIDERITE BANDS, MINOR COAL STRINGERS		BARREN MEASURES FORMATION		100
	SANDSTONE, SHALE, SILTSTONE, COMMERCIALLY EXPLOITABLE COAL SEAMS		BARAKAR FORMATION		700-1100
	TILLITE, BOULDER BED, CONGLOMERATE, SANDSTONE, SHALE, VARVE DEPOSITS	TALCHIR FORMATION		GLACIAL, BRAIDED RIVER	100-300
UPPER PALAEOZOIC	SEDIMENTARY DEPOSITS	OCCASIONALLY PRESENT			
PRE-CAMB	GRANITES AND METASEDIMENTS (BASEMENT COMPLEX)				

Figure A3.19 Summary of stratigraphy and lithology of the Damodar Basins (after Dutta 2002).

The Lower Permian Talchir Formation consists of tillite and other glacial deposits laid down in a braided river system. Overlying the Talchir are coal-bearing rocks of the Barakar Formation, deposited in a meandering river system. The Barakar coal measures gradually gave way to the non-productive strata of the Barren Measures Formation (largely sandstone and shale). In places, principally the Raniganj coalfield, these are overlain by Upper Permian coal measures of the Raniganj Formation, which were less widely deposited (Dutta 2002).

Triassic

Coal measure deposition continued into the Triassic resulting in the deposition of the Panchet Formation, which consists of sandstone, grey and red shales, with only rare coal seams. A relatively short erosional period occurred at the end of the Triassic before deposition of the Jurassic Mahadeva Formation took place.

Jurassic

The Mahadeva Formation consists largely of conglomerates, sandstones and siltstones. It is described as a mineralogically mature unit deposited in a braided river system (Dutta 2002).

Oil and Gas

No oil or gas fields have yet been found in the Damodar Valley basins.

CO_2 storage potential

The Damodar Valley basins may have potential for CO_2 storage, especially in areas where the coal measures are deeply buried beneath Mesozoic cover and thus less likely to be mined. Potentially, both reservoir rocks and seals are present in the Permian succession and thus the Damodar Valley is classified as having fair potential. However, there is insufficient information on structure, porosity and permeability of the potential reservoir rocks to make a judgement on their true potential.

References

Bhattacharyya, A. & Banerjee, S.N. 1979. Quaternary geology and geomorphology of the Ajay-Bhagirathi valley, Birbim and Murshidabad districts, West Bengal. *Indian Journal Earth Sciences*, **6**, 91-102.

Biswas, S.K. 1992. Tectonic Frame-work and Evolution of Graben Basins of India. *Indian Journal of Petroleum Geology,* **1**(2), 276-292.

Dutta P. 2002. Gondwana Lithstratigraphy of Penninsular India. Gondwana research (Gondwana Newsletter Section) **5**(2) pp540-553

Matter, J. M., Assayag, N. and Goldberg D. 2006 Basaltic rocks and their potential to permanently sequester industrial carbon dioxide emissions *in* 2006 8th International conference on greenhouse gas control technologies, Trondheim, Norway.

Parkash, B. & Kumar, S. 1991. The Indogangetic Basin. In: Tandon, S.K., Pant, C.C. & Casshyap, S.M. (editors), Sedimentary basins of India: Tectonic Context. Gyanodaya Prakashan, Nainital, India, pp 147-170.

Parkash, B., Sharma, B.P. & Roy, 1980. The Siwalik Group (Molasse) – sediments shed by collision of continental plates. *Sedimentary Geology*, **25**, 127-159.

Raiverman, V., Ganju, J.L. & Misra, V.N. 1979. A new look into the stratigraph of Cenozoic sediments of the Himalaya foothills between the Ravi and Yamuna rivers. *Geological Survey of India Miscellaneous Publications*, **41**, 233-246.

Raju, A.T.R. 1979. Basin Analysis and Petroleum Exploration with some examples from Indian Sedimentary Basins. *Journal Geological Society of India*, **20**, 49-60.

Shastri, V.V., Bhandari, L.L., Raju, A.T.R. & Datta, A.K. 1971. Tectonic framework and subsurface stratigraphy of the Ganga Basin. *Journal Geological Society India*, **12**(3), 222-233.

Srinivasan, S. & Khar, B.M. 1995. Frontier Basin Exploration in India – Perspectives and Challenges. *Proceedings PETROTECH-95, Technology Trends in Petroleum Industry*, New Dehli, pp1-19.

Vijaya and Bhattacharji, T. K., 2002. An Early Cretaceous age for the Rajmahal traps, Panagarh area, West Bengal: palynological evidence. Cretaceous Research **23**, pp 789–805.

THE GANGA BASIN

Introduction

A major Cenozoic foreland basin covering an area of over 750,000 km^2 lies immediately south of the Himalaya, Karakoram and Hindu Kush mountain ranges. It is the largest sedimentary basin in the subcontinent (Parkash & Kumar, 1991) and originated as a result of the collision of the Indian Plate with the Eurasian Plate in Cenozoic times. For descriptive purposes it is divided into three sections. From west to east these comprise the Indus Basin, the Punjab Shelf and Ganga Basin and the Assam Basin. The Ganga Basin is described below.

The Ganga Basin (Figure A3.20) lies to the south of the main boundary thrust of the Himalayas. It covers an area of some 250,000 km^2 (Shastri et al., 1971; Srinivasan & Khar, 1995).

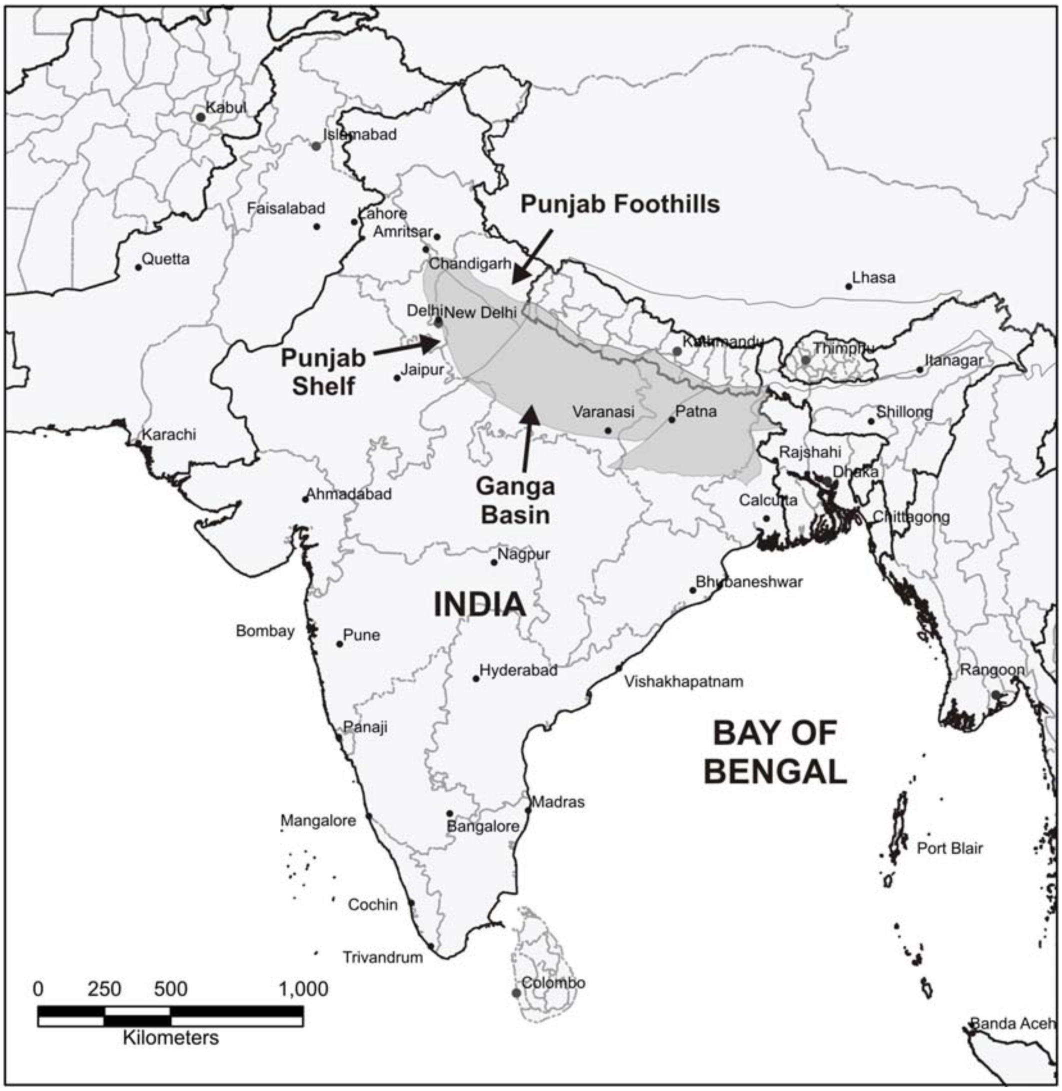


Figure A3.20 Location of the Ganga Basin and Punjab Shelf

To the east the Ganga Basin passes laterally into the Cainozoic and Quaternary alluvium north of the Shillong Plateau and then into the Assam Basin. To the west it passes laterally into the Cainozoic and Quaternary strata of the Punjab Shelf: the boundary between the two basins is somewhat arbitrary but is here taken along the Delhi-Hardwar Basement Ridge.

The Ganga Basin contains, close to the main Himalayan Boundary Thrust on its northern margin, 4-6 km of Cenozoic and Quaternary alluvium that thins southwards and eastwards onto older sedimentary sequences of Mesozoic, Palaeozoic and Precambrian age, and Precambrian basement rocks. Pre-Cenozoic basins thus exist beneath the Cenozoic and Quaternary alluvial deposits of the Ganges plain. A map of depth to basement beneath the Ganga Basin is given in Raiverman et al. (1983).

Fewer wells have been drilled in the Ganga Basin and Punjab Shelf than in prospective areas elsewhere in India. By 1991, there had been only 15 deep exploration wells drilled in the entire Indian section of the Indogangetic Plains.

Structure

The subcrop beneath the Cainozoic and Quaternary Ganga Basin consists mainly of concealed Proterozoic Vindhyan Basin fill and Archaean basement rocks.

As the collision between the Indian and Eurasian plates has progressed and the Main Central Thrust front has advanced southwards, the Ganga Basin depocentre has shifted gradually southwards. Cenozoic sediments deposited in the northern part of the basin, close to the thrust front have been folded and uplifted by the developing thrusts, forming the Siwalik Fold Belt (expressed as the Siwalik Hills). The strata in the southern part of the basin dip and thicken gently to the north.

The basin depocentre trends WNW. It can be subdivided into a series of smaller NE-SW trending sub-basins separated by ridges. The location of these structures reflects major basement features traversing the Indian craton, which can be traced northwards into the Himalayan region (Raju, 1979).

Monghyr-Saharsa Ridge

The eastern end of the Ganga Basin is defined by the Monghyr-Saharsa Ridge. It is a NNE-trending basement high with perhaps no more than 3 km of Siwilak strata lying directly upon basement (Shastri et al., 1971).

East Uttar Pradesh Shelf and Gandak Depression/Basin

The Gandak Depression and East Uttar Pradesh Shelf lie between the Monghyr Ridge to the east and the Faizabad Ridge to the west. Outcropping Vindyhan Group and basement form the southern boundary. To the north the shelf merges with the Gandak depression/basin, where the thickness of the sedimentary sequence increases to 6000 m or more. The basement is thought to be formed mainly by the Satpura Fold belt (Shastri et al., 1971)

In the deepest parts of the Gandak Depression, Mesozoic strata may be present, as a well near Raxaul proved the pre-Siwalik unconformity at 4128 m beneath which was a 67 m thick sequence of uncertain stratigraphic affinity lying above 607 m of strata assigned to the Vindyhan Group.

Faizabad Ridge

The Faizabad Ridge is a major north-easterly trending intrabasinal high. It is the concealed extension of the exposed Bundelkhand Massif.

West Uttar Pradesh Shelf and Sarda Depression/Basin

The West Uttar Pradesh Shelf is perhaps the best understood sub-basin area. At least 6 wells have been drilled and significant amounts of geophysical data have been acquired. To the NE it merges with the Sarda Depression/Basin. The pre-Siwalik unconformity varies in depth from 620 m near Kasgani to perhaps greater than 4,200 m near the Indo-Nepal border (Shastri et al. 1971).

Deli-Hardwar Ridge

The Deli-Hardwar Ridge marks the north-western limit of the Ganga Basin. The basement is shallow and is imaged on seismic reflection data as far NE as the Meerut region.

Stratigraphic and sedimentary details

The oldest sedimentary rocks, beneath the Ganga Basin and Punjab Shelf, which are of Upper Proterozoic to Lower Palaeozoic age, unconformably overlie crystalline basement. They are a series of shallow water platform or shelf limestones, shales and quartz-arenites that are assigned to the Vindyhan Group.

In the Gandak, and possibly the Sarda, Depressions the Vindhyan rocks are overlain by a thin sequence of unknown, possibly Mesozoic, age (Raju, 1979). But in general, Cenozoic strata lie unconformably on a peneplained surface of Vindyhan Group and basement rocks.

Cenozoic deposition commenced with sequences of the Sirmur Series. This is of Palaeogene age.

Over the greater part of the basin the Sirmur Series is overlain by the continental sands and silts of the Lower, Middle and Upper Siwalik Series of Neogene (Mid Miocene to Pliestocene) age, which onlap the Vindhyans and Basement. The thickness of the Siwalik Group varies from a few metres at the southern margin of the basin, to over 4000 m near the mountain front (Shastri et al. 1971). It consists of fluvio-deltaic sediments deposited by southerly flowing rivers draining into the Ganga basin from the Himalayas to the north.

The Cenozoic sediments of the Indogangetic Plain area have, due to exposures in the outer Himalayan belt, been well studied (e.g. Raiverman et al., 1979; Parkash et al., 1980; Parkash & Kumar, 1991). Given the tectonics in the area and continental deposition, local correlations are often difficult, however, the basic stratigraphic subdivisions are:

<table>
<tr><td rowspan="3">Neogene</td><td rowspan="6">Sub-Himalayan System</td><td rowspan="3">Siwalik Series (Supergroup)</td><td>Upper</td></tr>
<tr><td>Middle</td></tr>
<tr><td>Lower (Nahan)</td></tr>
<tr><td rowspan="3">Palaeogene</td><td rowspan="3">Sirmur Series</td><td>Upper (Kasauli)</td></tr>
<tr><td>Middle (Dagshai)</td></tr>
<tr><td>Lower (Subatha)</td></tr>
</table>

Details of the Lower Siwalik

The Lower Siwalik typically comprises highly indurated, compact, fine to coarse grained, grey to bluish grey and purple sandstones interbedded with reddish brown to grey, hard concretionary shales (Parkash et al. 1980). A maximum thickness of c. 2400m is found in the Kotdwara section to the east of Hardwar, where the uppermost 500 m of the sequences is arenaceous. This contains coarse sandstones and some conglomerates with pebbles 1-2 cm in size. Shales are thin and infrequent/almost absent (Parkash et al. 1980).

Southwards, away from the Himalaya, the Lower Siwalik sequences are a sandstone-clay assemblage, with often thick clay beds (Parkash et al. 1980).

Details of the Middle Siwalik

The Middle Siwalik comprises dominantly medium to coarse-grained, friable, cross-bedded sandstones, interbedded with some thin clay beds. Patches of calcite-cemented sandstones form more resistant areas at outcrop. The clays are earthy grey to purple red in colour.

The Middle Siwalik sandstones coarsen upwards, with a near absence of shales and the occasional appearance of conglomerates. In the north of the foldbelt area, the Middle Siwalik sandstones pass into mainly coarse conglomerates (Parkash et al. 1980). Southwards away from the Himalaya, as with the Lower Siwalik sequences, the Middle Siwalik is represented by a sandstone-clay assemblage, with often thick clay beds (Parkash et al. 1980).

Details of the Upper Siwalik

The Upper Siwalik is characterised by conglomerates consisting of pebbles set in an orange-red clayey or sandy matrix. A few shale interbeds are developed (Raju 1967, Raiverman et al. 1975).

The very coarse nature of the Upper Siwalik sequences, along with the near absence of clays, indicates a braided stream environment of deposition for the main part. A similar origin is envisaged for the arenaceous facies of the Lower and Middle Siwalik sediments.

Quaternary strata

The Quaternary sediments of the Indogangetic Plains are subdivided into the Older (Bhangar) and Younger (Khadar) Alluvium. There is evidence that they in places they can be further subdivided into Lateritic Upland, Older Deltaic Plain, Younger Deltaic Plain and Bhagirithi Recent Surface (Battacharyya & Banerjee, 1979). The modern Ganga system is a large braided river.

Well summaries

The following provide summaries of the general stratigraphy and rock type encountered across the Ganga Basin.

Raxaul #1

Sequence	*depth range*	*sediment type*
Allluvium & Upper Siwalik	0m – 1500 m	grey coarse to medium and pebbly sandstones, friable with Sub ordinate clay, overlain by alluvial sand and silt
Middle Siwalik	1500 m – 3200 m	Light grey, medium to fine grained sandstones with mottled

		siltstone and clay. Some carbonaceous streaks and fossil wood
Lower Siwalik	3200 m – 4128 m	brown calcareous claystones with siltstone and fine sandstone
---	*unconformity*	---
*M*esozoic	4128 m – 4195 m	reddish brown quartzitic sandstone with brown shales with bluish green variegations
Vindhyan	4195 m – 4901 m	current bedded orthoquartzites, some pebbly and conglomeritic, with metaquartzitic pebblesand thin green to purple shale lenses. Basic igneous rocks are present between 4195-4315 m and 4365-4410 m.

Ujhani #1

Sequence	*depth range*	*sediment type*
Allluvium & Upper Siwalik nodular clays	0 m – 705 m	Pebbly and coarse, highly micaceous, grey sandstones with
Middle Siwalik	705 m – 1016 m	coarse to medium grained Sandstone with variegated claystones and some carbonaceous streaks. Conglomerate developed above unconformity
---	*Unconformity*	---
	1010 m –1269 m	grey-greenish/grey dolomitic lst with fractures and intra-formational brecciation
	1269 m –1500 m	reddish brown quartz arenite with thin limestone bands towards base
Palaeozoic	1500 m – 1740 m	dark grey-brown pyritic shales with thin siltstone bands and brown shales towards top
	1740 m – 1804 m	reddish brown argillaceous lst with convolute bedding and slump structures
	1804 m – 1062 m	medium grained quartzwacke

with quartz arenite bands and thin laminae of grey shales

---*Unconformity*--

Precambrian	2062 m – 2127 m	metaquartzite with sericite schist and phllite

The quartz-arenite-limestone-shale sequence is assigned to the Palaeozoic, showing similarities with a similar sequence proved in the Tilhar well (Shastri et al., 1971).

Wells drilled to the SW of Badaun (near Kasannj) and Tilhar to the east of Badaun, proved similar sequences to the two wells above. However, at Kasanj, the carbonate section contains several anhydrite layers indicating local evaporitic conditions within the shallow marine area.

Hydrocarbons

There are few hydrocarbon exploration wells in this basin and therefore rock properties and hydrocarbon potential are poorly known.

A gas seep is recorded from the Middle Siwalik rocks in the Mindalti syncline in the foothills area. An exploration well testing the Tilhar structure encountered small amounts of gas in the Vindyhan sequence.

CO_2 storage potential

The Cainozoic and Quaternary basin contains the largest groundwater reserve in the country, which supports up to one third of the country's population (Parkask & Kukar, 1991), i.e. approximately one third of a billion people. Thus any CO_2 storage in the Ganges Basin would need to consider potential conflicts of interest with water supply.

Numerous aquifer units (fine-coarse grained sandstones and conglomerates) are present throughout the Cenozoic sequence, some of which provide the aquifers for the major towns and cities in the region. Potential traps exist in the Siwalik ranges and over the northern areas of the Indogangetic plain, some of which have been tested by exploration wells.

However, opportunities and potential for CO_2 storage in the Ganga Basin appear limited because the main sandstone aquifers provide the groundwater for both agriculture and major centres of population. Consequently, the huge reliance on the aquifer rocks for water supplies may render the area unsuitable, given the risk of possible contamination of the aquifers. Also, whilst potential reservoir sandstones exist, the development of shales that could form potential cap rocks is patchy and unpredictable.

References

Bhattacharyya, A. & Banerjee, S.N. 1979. Quaternary geology and geomorphology of the Ajay-Bhagirathi valley, Birbim and Murshidabad districts, West Bengal. *Indian Journal Earth Sciences*, **6**, 91-102.

Parkash, B. & Kumar, S. 1991. The Indogangetic Basin. In: Tandon, S.K., Pant, C.C. & Casshyap, S.M. (editors), *Sedimentary basins of India: Tectonic Context.* Gyanodaya Prakashan, Nainital, India, pp. 147-170.

Parkash, B., Sharma, B.P. & Roy, 1980. The Siwalik Group (Molasse) – sediments shed by collision of continental plates. *Sedimentary Geology*, **25**, 127-159.

Raju, A.T.R. 1979. Basin Analysis and Petroleum Exploration with some examples from Indian Sedimentary Basins. *Journal Geological Society of India*, **20**, 49-60.

Raiverman, V., Ganju, J.L. & Misra, V.N. 1979. A new look into the stratigraph of Cenozoic sediments of the Himalaya foothills between the Ravi and Yamuna rivers. *Geological Survey of India Miscellaneous Publications*, **41**, 233-246.

Shastri, V.V., Bhandari, L.L., Raju, A.T.R. & Datta, A.K. 1971. Tectonic framework and subsurface stratigraphy of the Ganga Basin. *Journal Geological Society India*, **12**(3), 222-233.

Srinivasan, S. & Khar, B.M. 1995. Frontier Basin Exploration in India – Perspectives and Challenges. *Proceedings PETROTECH-95, Technology Trends in Petroleum Industry*, New Delhi, pp1-19.

THE JAISALMER BASIN

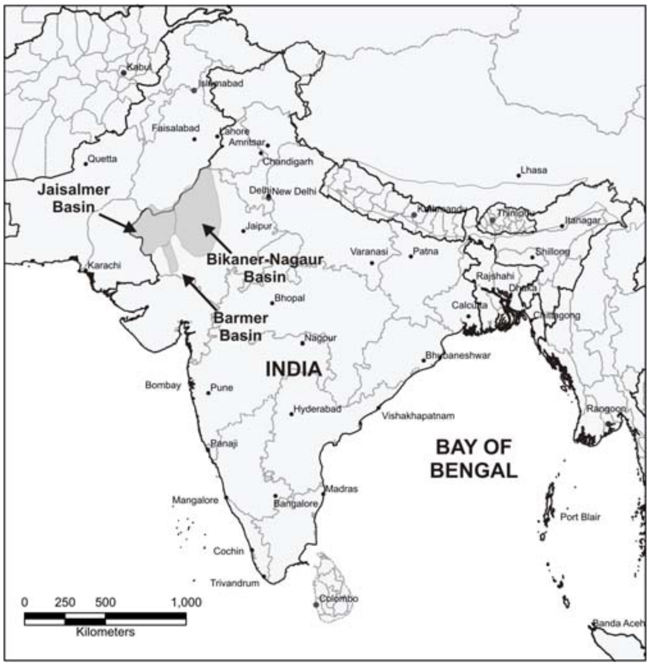


Figure A3.21 Location of the Jaisalmer Basin

Introduction

The Jaisalmer and Bikaner-Nagaur basins (Figure A3.21) are essentially Late Palaeozoic to Mesozoic basins underlying the easternmost part of the Cenozoic Indus Basin (which is known as the Indus Shelf). The Indus Basin lies mostly in Pakistan, where it contains thicker sequences and is hydrocarbon-bearing, containing both oil (e.g. Karampur) and gas (e.g. Sui and Mari) fields.

The Jaisalmer Basin lies in the extreme west of Rajasthan, northwest of the Barmer Basin, adjacent to the border with Pakistan. It covers an area of about 30,000 km^2. A partial, seismically-based map of the basin is presented by Datta (1983).

Stratigraphy

The main sedimentary sequence in the basins is of Permian to Cretaceous age, although the oldest rocks present are Cambrian. During Palaeogene times sedimentation rates slowed and Neogene sequences are thin or even absent across much of the basin.

Structure

The Jaisalmer Basin contains a series of intrabasinal highs and sub-basins (Figure A3.22) which are, from north to south: the Kishangarh sub-basin, the Jaisalmer-Mari High, the Shahrgarh sub-basin, and the Miajlar sub-basin. It adjoins the Barmer Basin (described in Figure A3.22 as the Bikaner-Sanchor Graben).

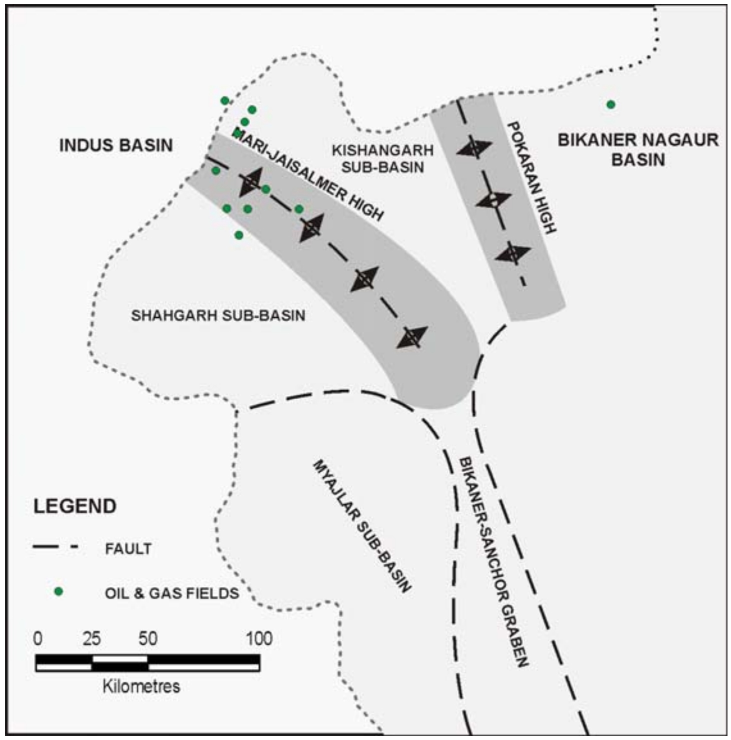


Figure A3. 9 Structural elements of the Jaisalmer Basin (adapted from Uniyal et al. 1997, Srivasatava et al. 1995, Ministry of Petroleum and Natural Gas 1991).

The Kishangarh subbasin is bounded by the Pokoran Ridge in the NE, which separates it from the Bikaner-Nagaur Basin, and by the Jaisalmer-Mari High to the SW. The maximum thickness of sediments in the basin is about 7 km.

The Jaisalmer-Mari High, originally recognised as a NW-trending basement ridge from a series of linear and parallel gravity highs, represents a complex faulted area rather than a simple upwarp of basement affecting the overlying sediments (Datta, 1983). It is the result of a series of NW-SE trending en echelon wrench faults on either side, stepping the basement up. These affected sedimentation during Mesozoic and Cenozoic times (Khar, 1984).

The Shahrgarh sub basin lies to the SW of the Jaisalmer-Mari High and contains up to 9 km of sedimentary rocks.

The Miajlar sub basin is a little explored marginal area located in the south of the Jaisalmer Basin and recognised mainly from the interpretation of remote sensing and potential field data (Mitra et al., 1993; Mukherjee et al., 1995). The basin covers an area of around 3400 km^2 and is bounded in the east by a NW-SE trending fault marking the northern margin of the Barmer Basin. To the north, it is separated from the Shahrgarh Basin by an E-W terrace-like feature in the basement. Some seismic reflection data have been acquired across the area and reveal units with strong, continuous reflections interpreted as arising from Lower Palaeozoic (Vindhyan) strata. The Lunar #1 well in the northernmost reaches of the basin has proved some of the concealed strata in the basin (Mukherjee et al., 1995).

Stratigraphic and sedimentological details

In the Jaisalmer Basin, eight sedimentary cycles have been recognised beginning with sequences of the Upper Proterozoic (Vindhyan) and including Indus alluvium of Quaternary age (Datta, 1983).

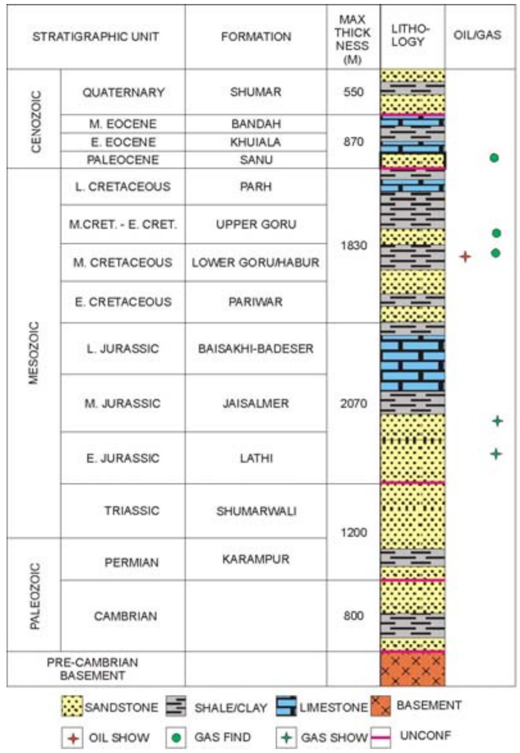


Figure A3.23 Summary stratigraphy of the Jaisalmer Basin

Sediments from the Proterozoic-Early Palaeozoic cycle (the Birmania/Randa Formations) are thick and represent deeper water sediments, when compared to those deposited in other basins of this age in India. However, exact age relationships and correlation of sediments between sub basins requires further work. Facies types indicate deposition in an extensive epicontinental sea during an arid period (Datta, 1983).

A major hiatus between the first and second cycle represents an orogenic phase resulting from plate collision, following which deposition of the shallow marine Permian Karampur Formation took place as the Indus shelf was inundated by a marine transgression.

The third phase, during Triassic and early Jurassic times, resulted in the deposition of predominantly continental fluvial to brackish deltaic clastic sequences. These are represented by the Shurmarwali and Lathi formations (Lukose, 1972).

During Middle Jurassic to Lower Cretaceous times an extensive stable shelf developed and carbonates were deposited widely. These exceed 1200 m in thickness in places. The basal carbonates contain considerable clastic material, but are cleaner higher up. In late Jurassic times the platform stability may have been disturbed as intense igneous activity commenced close by and further clastic material, represented by the Baisakhi and Badasar formations, entered and was deposited in a shallow marine basin. The Lower Cretaceous Parimar Formation represents a regressive phase with earlier sequences deposited in shallow marine and brackish conditions and culminating in continental conditions towards the top.

The fifth (Aptian – Albian) cycle commenced with deposition of the shallow marine Harur Formation represented by marls and arenaceous limestones along the basin margin and the Goru Formation comprising mainly marine clastics more basinwards. Sedimentation continued until Coniacian times with the development of a predominantly marine marl and carbonate succession, with some clastic beds. A major uplift phase driven by events to the west led to a prominent hiatus in sedimentation from Danian to Lower Palaeocene times. Considerable erosion of the Cretaceous succession occurred along the basin margin during this period.

The sixth sedimentary cycle commenced with the deposition of the clastic-dominated Sanu Formation, representing brackish to shallow marine conditions in late Palaeocene times. The transgression continued into early Eocene times as a series of fine clastics, marls and carbonates of the Khuiala and Bandah formations were deposited during relatively stable conditions. Renewed uplift to the west commenced during Oligocene times and a major regressive phase ensued.

From mid Miocene times, subsidence of the Indus shelf resumed with cycles 7 and 8 represented by deposition of molasse sediments from Middle Miocene to Pliocene times as a result of the onset of the Himalayan orogenic phase. Subsequently the Jaisalmer Basin was uplifted and underwent erosion and supplied clastics to the west and southwest until Quaternary times. Since Quaternary times a thin veneer of fluvial sediments has been laid down unconformably over Middle Miocene strata.

Hydrocarbons

Regional seismic reflection surveys have been acquired across the basin and exploration wells have led to the discovery of several commercial gas fields (Datta 1984). Some light oil has also been encountered, but has yet to be found in commercial quantities. The hydrocarbon potential of the western areas - the Kishangarh and Shahrgarh sub-basins - is generally thought to be good.

Hydrocarbon exploration has concentrated on the flanks of the Jaisalmer-Mari High and most of the structures have shown the presence of gas. Non commercial oil has been found in the Dandewala structure.

Characterisation of gases has proved two different types: those accumulated in Cenozoic (Palaeocene/early Eocene) reservoirs are a mixture of locally formed bacterial gases and thermogenic gas. In Early Cretaceous reservoirs, the gases are thermogenic (Uniyal et al., 1997).

CO_2 storage potential

The Jaisalmer Basin has good potential for CO_2 storage, particularly in the Kishangarh and Shahrgarh sub basins where a number of gas fields have already proven reservoir and cap rocks in suitable trapping configurations.

References

Datta, A.K. 1983. Geological Evolution and Hydrocarbon Prospects of Rajasthan Basin. *Petroleum Asia Journal*, November 1983, 93-100.

Khar, B.M. 1984. Tectonic framework and hydrocarbon entrapments of Rajasthan Shelf. *Bulletin ONGC*, **21**(1), 13-21.

Luckose, N.G. 1972. Palynologocal evidence on the age of the Lathi Formation, Western Rajasthan, India. *Proceedings Seminar on Palaeopalynology and Indian Stratigraphy*, pp155-159.

Mitra, D.S., Bhoi, R. & Agarwal, R.P. 1993. Hydrocarbon exploration in Shargarh and Myajlar subbasins of Jaisalmer Basin, Rajasthan, India using remote sensing techniques. *Indian Journal Petroleum Geology,* **2**(1), 31-42.

Mukherjee, B.K., Bhandari, S.K. & Purkayastha, D. 1995. Hydrocarbon Prospects and evidence of Presence of Proterozoic Basin in Lunar-Miajlar Area, Rajasthan. *Proceedings of PETROTECH-95, New Delhi Technology Trends in Petroleum Industry,* pp.133-145.

Uniyal, A.K., Dwivedi, P., Mittal, A.K., Banerjee, V. & Chandra, U. 1997. Genetic Characterisation and Correlation of Natural Gases in Jaisalmer Basin, India. *Proceedings of Second International Conference and Exhibition, Petrotech 97*, New Delhi, pp. 117-120. B.R. Publishing Corporation, New Delhi.

THE KONKAN-KERALA BASIN

Introduction

The Konkan- Kerala Basin forms the southern part of the western continental margin of India (Figure A3.27). It covers an area of approximately 77,000 km^2 down to the 200 m isobath and about 92,000 km^2 down to the 2000 m isobath (Singh & Lal 1993).

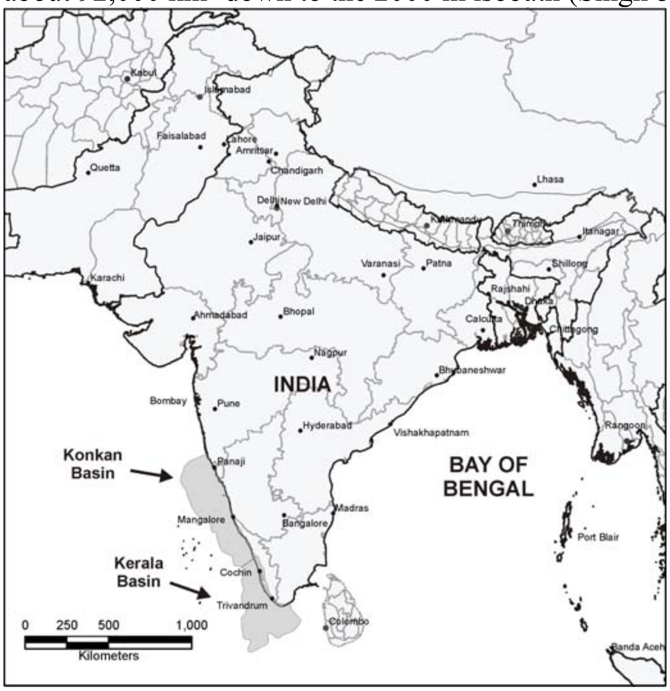


Figure A3. 24 Location of the Konkan-Kerala Basin

Eight wells had been drilled in the basin to 1993. No discoveries were made although some hydrocarbon shows were observed (Singh & Lal 1993).

Structure

The onshore area

Only a very small part of the basin is onshore. Neogene and Quaternary sedimentary rocks, generally less than 300 m thick, rest directly on Precambrian basement in the area around Cochin and Trivandrum.

The offshore area

The offshore part of the Konkan-Kerala basin can be divided into six contiguous structural elements (see Singh & Lal, 1993 for map and cross section). From onshore to offshore these comprise: the Shelfal horst-graben complex, Kori-Comorin Depression, Kori-Comorin Ridge, Laxmi-Laccadive Depression, Laxmi-Laccadive Ridge and Arabian Abyssal Plain. The basin's boundary with the contiguous Mumbai Basin to the north is taken at the Vengurla Arch, a SW-plunging basement arch.

The basin developed as a result of an early Rift Phase that is thought to have terminated in pre-Santonian times (Singh & Lal 1993) and a Post-Rift Phase that followed. Thus, during the Late Cretaceous to Early Palaeocene, and subsequently, sedimentation took place in response to passive subsidence of the continental margin and basinwards tilting of the depositional surface.

Stratigraphy

Figure A3.25 summarises the stratigraphy of the Konkan-Kerala Basin.

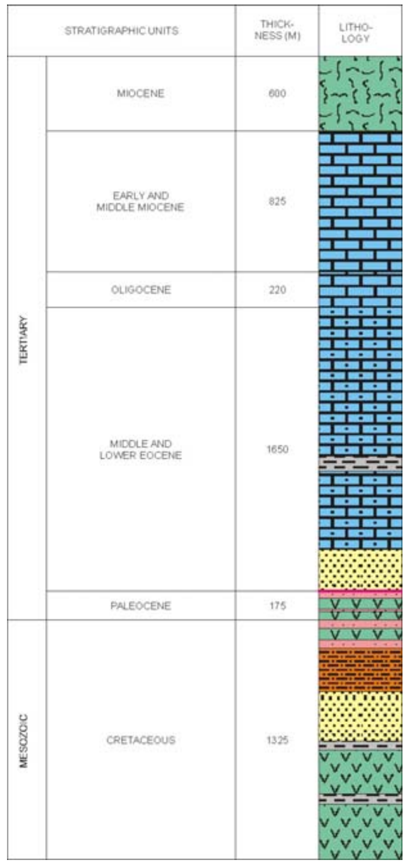


Figure A3.25 Generalised stratigraphy of the Konkan-Kerala Basin

The oldest drilled strata in the basin are Cretaceous volcanics. They are overlain by shallow water limestones, sandstones and silts. Santonian to Maastrichtian clastics are present in one of the wells. Latest Cretaceous to Palaeocene volcanics, equivalent in age to the Deccan Traps, overlie these (Ministry of Petroleum and Natural Gas, 1991; Desikachar, 1980).

A prograding shelf depositional system then developed. The Early Eocene to Middle Miocene shelf sediments consist predominantly of limestone and dolomite in the north of the basin, but include coarse clastics in the south.

Late Miocene to Recent sediments consist predominantly of shale and claystone but become sandier close to the coast.

Details of the stratigraphic succession in four of the wells are given in Singh & Lal (1993).

A deep sea borehole drilled on the eastern flank of the Laccadive Ridge penetrated 411m of Palaeocene terrigenous clastic and Eocene to Recent biogenic siliceous sediments and calcareous oozes but did not reach the ocean basalt underneath anticipated to be present at a depth of about 500 m below sea bed (Mitra et al., 1983).

In the north part of the area, a long narrow horst, the Kerala-Laccadive ridge, has been mapped (Mitra et al., 1983). This ridge, and the parallel Kerala-Laccadive Depression run for more than 2000 km N-S. The ridge is though to be composed of basalt. It is capped by recent coral reefs (Mitra et al., 1983).

Hydrocarbons

Source rocks

Boreholes drilled in the Kerala basin appear to indicate a near-absence of potential source rocks near shore. Moreover, no hydrocarbon shows have been found. Speculatively, there may be some potential further west where the sedimentary sequence is thicker (Mitra et al., 1983).

Reservoir rocks

On the southern part of the shelf, the Cochin-1 well encountered Palaeogene coarse sandstones and Miocene-Pliocene terrigenous clastics with coarse sandstones, claystones and numerous lignite streaks and minor limestone. The well bottomed in fractured basalt most likely of Late Cretaceous-Palaeocene age (Mitra et al., 1983).

Potential traps

Speculatively, the series of transgressions and regressions that deposited thick sediments in the basin from Palaeocene to end Miocene times may have formed stratigraphic traps, particularly on the shallower parts of the continental shelf (Desikachar, 1980). The region around the Laccadive and Minoy Islands shows evidence for the presence of upwarps and basins that form potential traps. The hinge zone adjacent to the outer continental shelf could have received hydrocarbons migrating upwards from the deeper oceanic parts of the sequence (Desikachar, 1980). The western shelf of the Kerala coast may have stratigraphic trap reservoirs within the carbonate sequence (Desikachar, 1980).

Additional information on existing wells

The Karwar-1 well, in the north of the Konkan Basin, was drilled on a fault-bounded horst block close to the edge of the Miocene paleoshelf. More than 1000 km of limestones and dolomitic limestones with good secondary porosity were penetrated. The borehole was abandoned due to complications (Mitra et al., 1983).

The Kasargod-1 well was drilled on the flank of a sharp carbonate buildup in the southern part of the Konkan Basin. It penetrated over 1400 m of carbonates underlain by over 520 m of sand and clay. A minor gas show was noted but no major hydrocarbon shows were identified (Mitra et al. 1983).

The K-1-1 well in the northern part of the Kerala Basin (Figure 2) penetrated Oligocene-early Miocene limestones and sandstones at depths of 1200 m and deeper, capped by Mid-Miocene clays.

The CH-1-1 borehole in the central Kerala Basin penetrated Oligocene-Miocene carbonates at depths of more than 800 m capped by late Miocene clays.

The Cochin-1 well in the southern part of the Kerala Basin targeted a Cenozoic fault closure but there were no hydrocarbon shows (Mitra et al. 1983).

CO_2 storage potential

Onshore, Cenozoic cover deposited on Precambrian basement is generally less than 300 m thick (Bose et al. 1980) and therefore unsuitable for CO_2 storage.

Poor porosity in wells drilled in the Kasargod and Karwar areas, due to cementation and dolomitisation (Sharma et al. 1986), may rule them out as reservoirs for CO_2 storage. However, there might be opportunities in the sandstones identified in some of the other wells.

The Late Miocene-Recent section consists mainly of clays and shales in the deeper parts of the basin, and appears likely to form an excellent cap rock.

In general, opportunities to store CO_2 in the offshore Konkan-Kerala basin appear to be limited.

References

Desikachar, S.V. 1980. Geology and hydrocarbon prospects of the Kerala west coast basin. *Bulletin ONGC,* **17**(1), June 1980, 25-34.

Ministry of Petroleum and Natural Gas 1991. India: Opportunities for oil and natural gas exploration. Ministry of Petroleum and Natural Gas, Government of India.

Mitra, P., Zutshi, P.L., Chourasia, R.A., Chugh, M.L., Ananthanarayanan, S. & Shukla, B. 1983. Exploration in western offshore basins. In: L.L. Bhandari, B.S. Venatachala, R. Kumar, S.N. Swamy, P. Garga & D.C. Srinastava (editors), *Petroliferous basins of India*. Petroleum Asia Journal, November 1983, pp15-24.

Singh, N.K. & Lal, N.K. 1993. Geology and petroleum prospects of Konkan-Kerala basin. In: Biswas, S.K., Dave, A, Garg, P., Pandey, J, Maithani, A., Thomas, N. J. (editors), *Proceedings of the second seminar on Petroliferous basins of India*, Vol. 2, India Petroleum Publishers, Dehra Dun, India, pp461-467.

THE KRISHNA-GODAVARI BASIN

Introduction

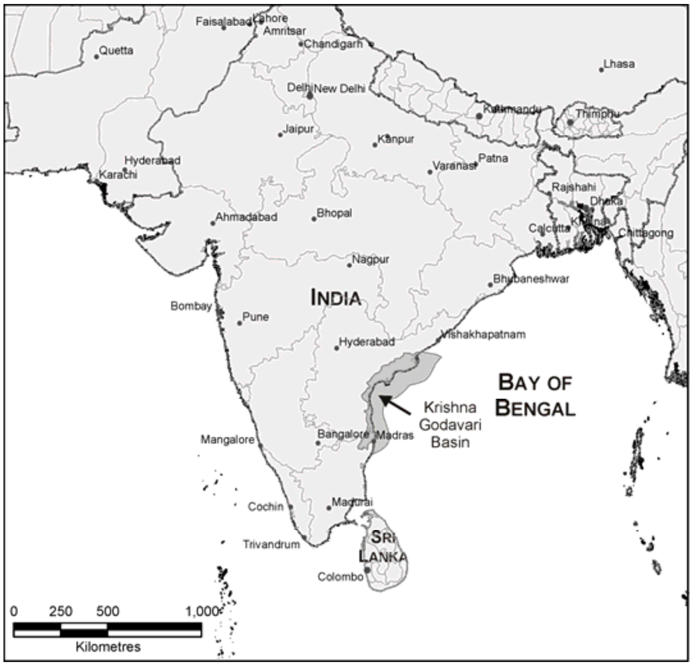


Figure A3. 26 Location of the Krishna-Godavari Basin

The Krishna-Godavari Basin is located on the east coast of the Indian peninsula (Figure A3.26). It is named after the two major river systems, the Krishna and Godavari systems, which drain through the basin, across a deltaic plain into the Bay of Bengal. The basin covers an area of approximately 45,000 km^2, of which about 20,000 km^2 lies onshore and about 25,000 km^2 offshore down to the 200 m isobath. It is one of India's most prolific hydrocarbon-producing basins: it is now clear that hydrocarbon prospectivity extends well below the 200 m isobath, into deep water in the Bay of Bengal, where a major gas discovery has recently been made (Gupta 2006).

The Krishna-Godavari Basin overlies the SE end of the Prahnita-Godavari Graben, a Gondwana graben filled with ?latest Carboniferous to Early Permian strata. Exposures of Precambrian rocks limit the basin to the south, west and northwest.

Structure

The Krishna-Godavari Basin was formed along the eastern passive, divergent, margin of the Indian craton when India split away from Australia and Antarctica in Early Cretaceous times. Structurally, the Basin consists of a series of en-echelon horsts and graben which divide it into a number of smaller sub-basins (Majumdar et al., 1995).

The Bapatla and Tanuku Ridges divide the onshore part of the basin into three sub-basins - the Krishna,West Godavari and East Godavari sub-basins (Figure A3.27). These are described in more detail below:

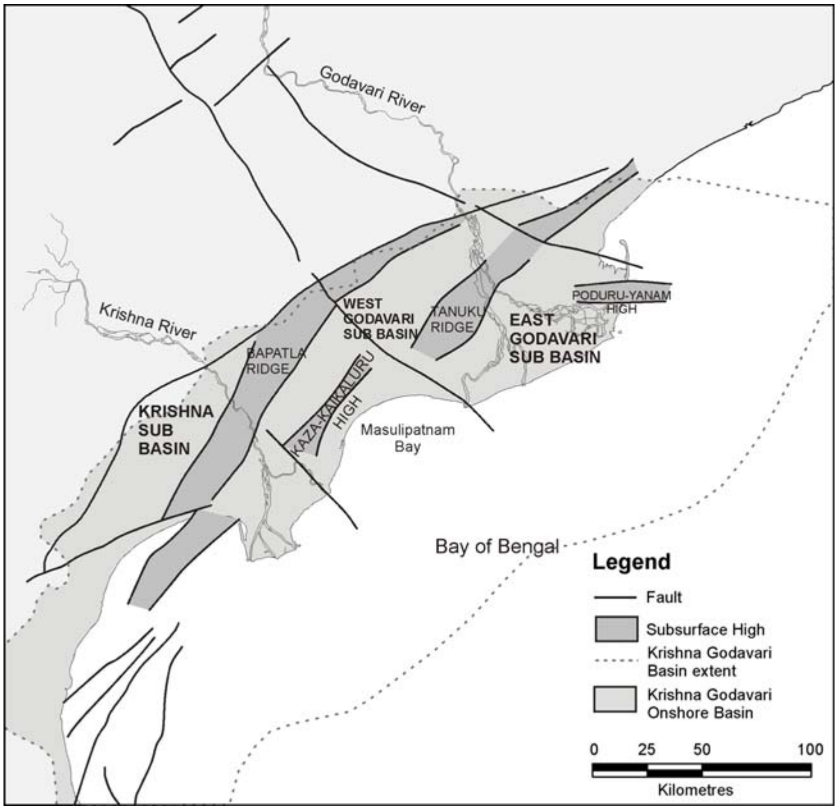


Figure A3.27 Map showing the sub-basins and horsts in the onshore and nearshore part of the Krishna-Godavari Basin (adapted from Ministry of Petroleum and Natural Gas 1991)

The Krishna sub-basin

The Krishna sub-basin is the most marginal (westernmost) part of the basin. It is in faulted contact with the surrounding Archean basement to the west. It contains predominantly Cretaceous and older strata.

The Bapatla ridge

The Bapatla ridge lies on the eastern side of the Krishna sub-basin. It extends in a NE-SW direction from onshore into the offshore. The depth to basement over the crest of the ridge is typically about 200 m, increasing to approximately 500 m in the southwest, and therefore probably too shallow for significant CO_2 storage. A series of faults lie on the south-eastern margin of the ridge, marking its boundary with the West Godavari sub-basin. Upper Gondwana sedimentary rocks with a thin covering of Miocene-Pliocene strata overlie basement on the ridge.

The West Godavari sub-basin

The West Godavari sub-basin consists of the Kaza-Kaikaluru horst, which remained uplifted during the early Cretaceous, and the Gudivada and Bantumilli grabens. The offshore part of the sub-basin is divided into three separate areas by two NW-SE cross-trends extending from onshore, (Chintalapudi and Avanigadda; Murthy et al. 1995). It is also characterized by a series of NE-SW-trending growth faults and associated Neogene rollover anticlines.

The Tanuku ridge

The Tanuku ridge separates the East and West Godavari sub-basins. Up to 2 km of sedimentary cover is present on top of the ridge (Verma et al. 1993), so it is deep enough for CO_2 storage if suitable reservoirs and seals are present.

The East Godavari sub-basin

The East Godavari sub-basin is filled by 2900-5000 m of sedimentary rocks. It contains en echelon faults formed during the Late Cretaceous-early Palaeocene (Rao, 2001). The onshore part of the sub-basin lies beneath the delta formed by the Godavari River and contains small sub-basins and basement highs (Verma et al. 1993).

5.4.2 Hydrocarbons

Hydrocarbons were first discovered in the Krishna-Godavari Basin in 1978 when an onshore well in the Upper Cretaceous Naraspur structure in the East Godavari sub-basin (Rao 2001) produced gas at 4035 m (Venkatarengan & Ray 1993).

The first offshore well, G-1-1, discovered oil and gas in Pliocene sandstone reservoirs. Since then accumulations of hydrocarbons have been discovered in Permian to Pliocene reservoirs (Gupta 2006). Major fields include the highly productive (offshore) Ravva oilfield.

Reliance has recently made a major gas discovery in deep water off the Krishna-Godavari basin.

Reservoirs and seals

The Mandepeta and Golapalli formations contain excellent sandstone reservoir rocks.

The Early Cretaceous Gollapalli Sandstone is locally sealed by clays (red beds) and more generally by the overlying Raghavapuram Shale, which is a regional seal (Rao, 2001).

The Krishna Formation and sandstone layers within the Kaikalur Claystone of Early/Late Cretaceous age have reservoir potential (Rao 2001). In the East Godavari sub-basin, there are Cretaceous reservoirs in the Parsarlapudi Formation and the Razole Volcanics (Venkatarengan & Ray 1993). There is also excellent potential offshore, as exemplified by the oil and gas discoveries there.

CO_2 Storage Potential

The Krishna-Godavari basin has excellent CO_2 storage potential both onshore and offshore, as the numerous hydrocarbon fields indicate the presence of traps that can retain buoyant fluids at several stratigraphic levels.

References

Gupta, S.K. 2006. Basin architecture and petroleum system of Krishna Godavari Basin, east coast of India. *The Leading Edge*, **25**(7), 830-837.

Majumdar, S. K., Basu, B., Shivasankar, J., Arunachalam, A. & Rangaraju, M. K. 1995. Palakollu-Pasarlapudi Petroleum System, Krishna-Godavari Basin, India. *Proceedings of PETROTECH-95, New Delhi Technology Trends in Petroleum Industry*.

Murthy, K.S.R., Subrahmanyam, A.S., Lakshminarayana, S., Chandrasekhar, D.V. & Rao, T.C.S. 1995. Some geodynamic aspects of the Krishna-Godavari basin, east coast of India. *Continental Shelf Research*, **15**(7), 779-788.

Prabakaran. S. and Ramesh, P. 1995. Basin Evolution, Stratigraphy and Depositional Systems in Krishna-Godavari Basin India. *Proceedings of PETROTECH-95, New Delhi Technology Trends in Petroleum Industry*, p229-249

Rao, G.N. 2001. Sedimentation, Stratigraphy, and Petroleum Potential of Krishna-Godavari Basin, East Coast of India. *Bulletin American Association of Petroleum Geologists*, **85**(9), 1623-1643.

Venkatarengan, R. & Ray, D. 1993. Geology and Petroleum Systems, Krishna-Godavari Basin. In: Biswas, S.K., Dave, A, Garg, P., Pandey, J, Maithani, A., Thomas, N. J. (editors), *Proceedings of the second seminar on Petroliferous basins of India*, **Vol. 1**, Indian Petroleum Publishers, Dehra Dun, India, p331-353.

Verma, R.K., Satya Narayana, Y. & Chander Sekhar Rao, S. 1993. Gravity Field, Tectonics and Evolution of Krishna-Godavari and Cauvery Basins of India. *Indian Journal of Petroleum Geology*, **2(**2), 39-72.

THE KUTCH BASIN

Introduction

The Kutch Basin (also known as the Kachchh Basin) is a Mesozoic rift basin on the western margin of the Indian craton (Figure A3.28) that is overlain by approximately 900 m of Cenozoic sedimentary rocks. Covering an area of around 71,000 km^2 (Ministry of Petroleum and Natural Gas 1991, Biswas 1982), the Kutch Basin comprises a series of fault blocks and half graben bounded by steep faults that follow Precambrian trends (Biswas 1982, 1987).

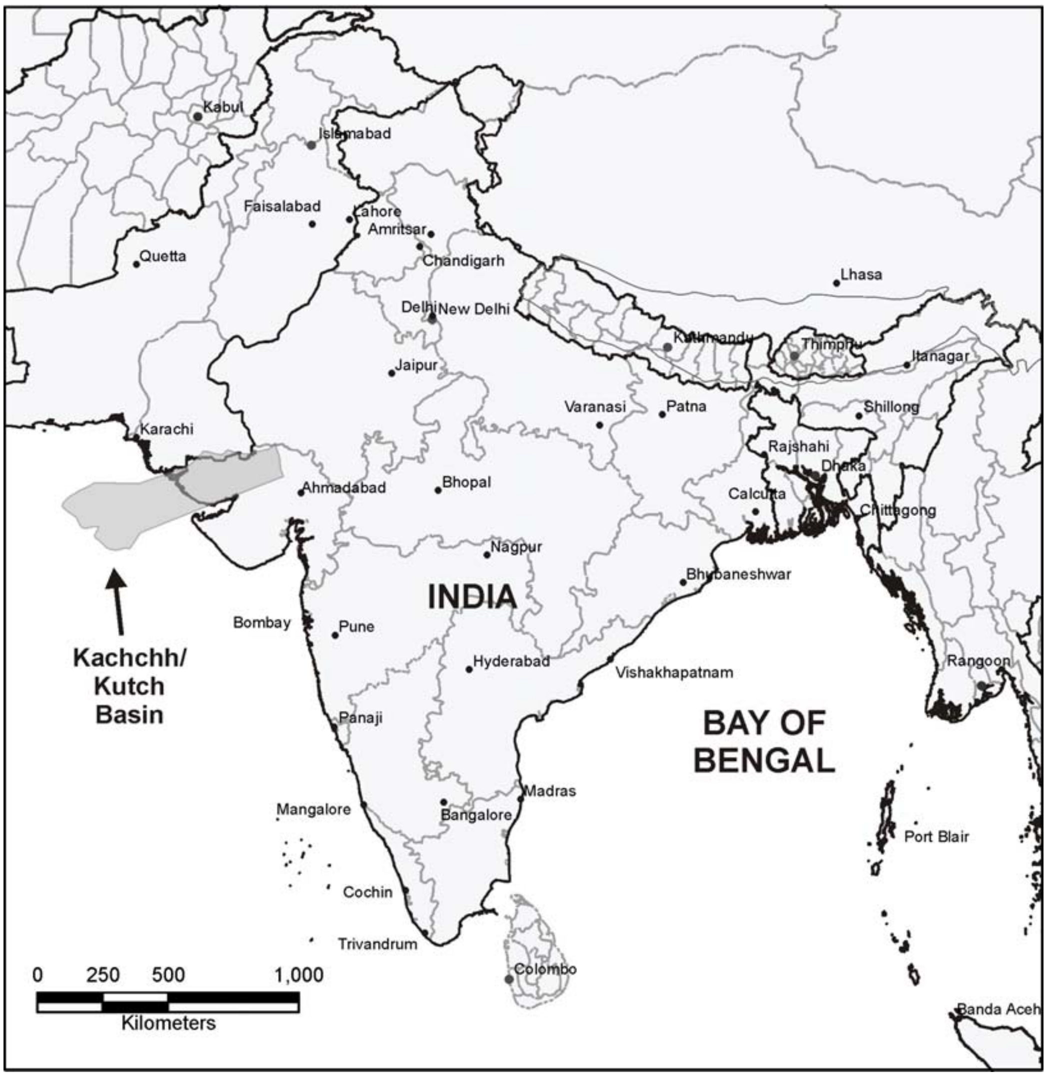


Figure A3.28 Location of the Kutch Basin

The basin contains over 3000 m of Mesozoic sedimentary rocks overlain by up to 900 m of Cenozoic sediments (Biswas 1991). Deccan Trap basalts cover the Mesozoic strata in the south of the Kutch Basin (Biswas & Deshpande 1973) and the Mesozoic strata in the basin are highly folded, faulted and intruded by igneous rocks (Biswas 1982).

Structure

To the NE, the basin is bounded by the margin of the Indian shield, to the SE it is bounded by the Kathiawar horst block and Saurashtra arch and to the North it is bounded by the Nagar-Parkar ridge (Biswas 1987). It is influenced by the NE-SW Precambrian Delhi-Aravalli faulting trends (Ministry of Petroleum and Natural Gas 1991). Passive basement ridges parallel to Precambrian faults were present during Mesozoic deposition and the faults were later reactivated during Cenozoic uplift (Biswas 1991). The Kutch offshore extension is a gently sloping platform with two regional highs; an extension of the E-W Kutch Mainland Uplift and a NW-SE trending high that follows the Dharwar trend. Mesozoic sediments are exposed in the northern "Island Belt" (Mitra et al. 1983).

Major unconformities in sequences of the Upper Palaeocene, post-Lower Eocene (Ypresian), Upper Eocene, post-Oligocene, Upper Miocene and Early Quaternary indicate relatively recent tectonic movements (Biswas & Deshpande 1983, Biswas 1982).

Hydrocarbons

Five onshore wells and 13 offshore wells have revealed an offshore non-commercial gas accumulation and a few offshore oil shows and onshore gas shows.

Offshore, over 2000m of coarse-grained Upper Palaeocene to Middle Miocene limestones were encountered in a well drilled in a large anticlinal closure. Gas and occasional oil shows were encountered in the Miocene section, with scattered oil shows and infrequent gas shows encountered in the underlying Eocene. The Miocene reservoirs appear to have been flushed (Mitra et al. 1983). Eocene lowstand fans and wedges have been identified on seismic as potential targets for hydrocarbon exploration (Dwivedi et al., 1995).

CO_2 storage potential

Over 900 m of Cenozoic sediments are underlain by more than 3000 m of Mesozoic strata (Biswas, 1991).

The Kutch basin is divided into three provinces:

- Kutch Mainland, near the basin depocentre
- Pacham Island (where deposition apparently ceased after the Mid-Callovian)
- Eastern Kutch

In the Kutch Mainland, the Upper Jurassic top Jhuran sandstones are potential reservoir rocks and buried to depths of around 800-1295 m (Biswas 1991). Therefore they are potentially suitable for CO_2 storage.

In the Pacham Island area, Mesozoic cover is too thin (<621 m, Biswas 1991) to be of interest for CO_2 storage.

In eastern Kutch, sands of the Jurassic Lower Khadir Formation are of sufficient depth (around 990 m - Biswas 1991) to be considered for CO_2 storage and they are capped by shales.

In summary, there is likely to be some potential for CO_2 storage in the Kutch basin but further study is required to firm it up.

References

Biswas, S.K. 1982. Rift basin in western margin of India with special reference to Kutch basin and its hydrocarbon prospects. *Bulletin American Association of Petroleum Geologists*, **66**(10), 1497-1513.

Biswas, S. K. 1987. Regional tectonic framework, structure and evolution of the western marginal basins of India. *Tectonophysics,* **135**, 307-327.

Biswas, S.K. 1991. Stratigraphy and sedimentary evolution of the Mesozoic basin of Kutch, western India. In: Tandon, S.K., Pant, C.C. & Casshyap, S.M. (editors), *Sedimentary basins of India: Tectonic Context.* Gyanodaya Prakashan, Nainital, India, 74-103.

Biswas, S.K. & Deshpande, S.V. 1983. Geology and hydrocarbon prospects of Kutch, Saurashtra and Narmada basins. In: L.L. Bhandari, B.S. Venatachala, R. Kumar, S.N. Swamy, P. Garga & D C Srinastava (editors), *Petroliferous basins of India*. Petroleum Asia Journal, November 1983, 111-126.

Das, B. & Patel, N.P. 1984. Nature of Narmada-Son lineament. *Journal Geological Society India*, **25**(5), 267-276.

Dwivedi, A.K., Thakur, R.K., Bajpai, A.K., Lal, N.K., Sarkar, S. & Srivastava, H.C. 1995. Sequence stratigraphy and systems tracts of Eocene and Miocene sediments in Kutch offshore, India. *Proceedings PETROTECH-95, Technology Trends in Petroleum Industry,* pp197-206.

Ministry of Petroleum and Natural Gas 1991. India: Opportunities for oil and natural gas exploration. Ministry of Petroleum and Natural Gas, Government of India.

Mitra, P., Zutshi, P.L., Chourasia, R.A., Chugh, M.L., Ananthanarayanan, S. & Shukla, B. 1983. Exploration in western offshore basins. In: L.L. Bhandari, B.S. Venatachala, R. Kumar, S.N. Swamy, P. Garga & D.C. Srinastava (editors), *Petroliferous basins of India*. Petroleum Asia Journal, November 1983, pp15-24.

Roday, P.R. & Singh, A.K. 1982. Great Boundary Fault: age, kinematic development model and rejuvenative episodes. (Abstract) *Seminar on Indian lithosphere: Structure and evolution, Poona Univ., Poona*, pp22-23.

THE LOWER INDUS BASIN

The Lower Indus Basin (Pakistan) covers an area of about 400,000 km^2. It contains several oil and gas discoveries, the largest of which is the Sui gas field (discovered in 1952, with estimated initial recoverable reserves of 8.624 tcf gas).

The basin lies on the western margin of the Indian Plate and deepens steeply to the west. Cross sections of the basin are shown in Kadri (1995). Its eastern margin is formed by the Punjab Shelf and Thar Platform, which are separated by the Jocobabad and Mari-Kandkhot Highs that lie partly in India. The central deepest part of the basin is known as the Sulaiman Depression in the northern part of the basin and the Karachi Trough in the south. The northern and central parts of its western margin are marked by the thrust faults of the Sulaiman and Kirthar fold belts. To the south, the basin extends offshore.

The Thar Platform contains well developed Early to Middle Cretaceous sands that form the reservoirs of all the gas fields in this region. The Punjab Shelf contains some major stratigraphic pinchouts. The Sulaiman depression contains some buried anticlines. The Karachi Trough, which opens up into the Arabian Sea, contains large numbers of anticlines, some of which form gas fields.

A summary of the characteristics of the reservoirs in the basin is given in Kadri (1995).

CO_2 storage potential

It is clear that there is significant CO_2 storage potential in several parts of the Lower Indus Basin, both in the major gas fields (when depleted) and in aquifers. However, its aquifers support a dense population heavily reliant on agriculture. Therefore there are likely to be conflicts of interest with any proposed CO_2 storage.

References

Kadri, I.B. 1995. *Petroleum Geology of Pakistan*. Pakistan Petroleum Ltd, Karachi, 275 pp.

THE MAHANADI BASIN

The Mahanadi Basin (Figure A3.29) developed along the eastern coast of India as a result of the separation of the Indian plate from Antarctica and Australia during Cretaceous times. It lies immediately south of the Bengal Basin and its south-western limit is marked by the prominent 85° East Ridge. The thickest sedimentary succession occurs in the northern part of the area shaded on Figure A3.29.

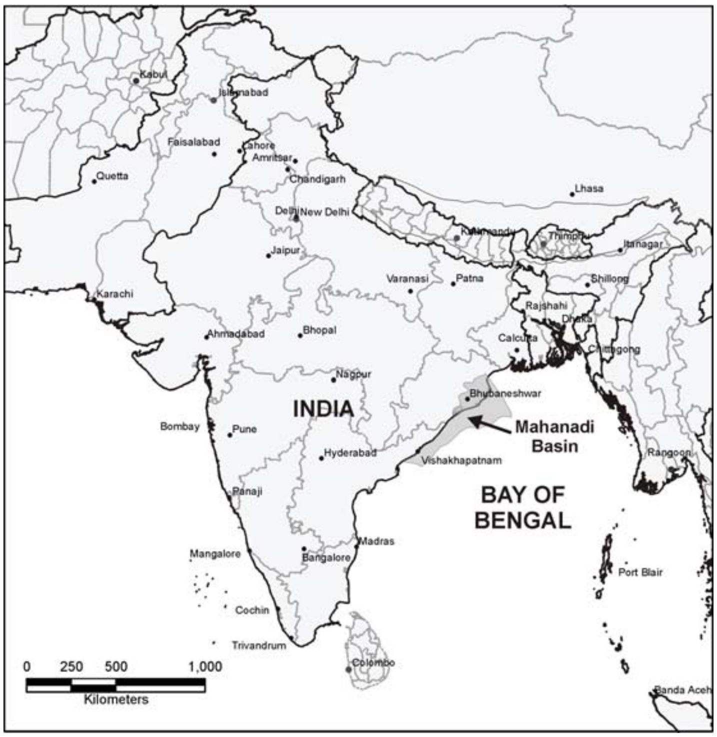


Figure A3.29 Location of the Mahanadi Basin

The basin as a whole is developed at the junction between the NE-SW-trending coast (a passive continental margin), and the northwest-southeast trending Mahanadi Graben within the Indian shield (Fuloria 1993). The Mahanadi Graben is a Permian/Mesozoic (Gondwana) structural feature.

Structure

The basin is characterised by numerous coast-parallel faults, cross-cut by a few NNW-SSE-trending faults that divide the basin into blocks. The northernmost cross-cutting fault marks the boundary between the offshore Mahanadi Basin and the Bengal Basin. Sinistral strike-slip displacement on this fault totals around 60 km.

Basin Evolution

The first occurrence of rifting, accompanied by subsidence of the Precambrian basement, may have been during Late Jurassic times, although the oldest rocks within the basin are Early Cretaceous volcanics (Fuloria 1993). During Late Cretaceous times, thick clastic sediments were deposited in the fault-controlled depressions in the offshore part of the basin, but virtually no sedimentation occurred onshore.

Early Palaeocene times were marked by a gentle tilting of the offshore basin towards the southeast. Deposition occurred in the offshore basin, but in the onshore basin there is no evidence of sedimentation during the entire Palaeocene-Eocene period (Fuloria 1993).

Upper Eocene to Oligocene strata are absent from all wells and are not encountered anywhere in the Mahanadi Basin (Fuloria, 1993). This is in contrast to the adjacent Bengal Basin, where extensive sedimentation occurred in Upper Eocene to Oligocene times.

Regional subsidence restarted in Miocene times, with evidence of marine transgressions in both the offshore and onshore areas. A high subsidence rate during Middle Miocene times coincided with the rapid uplift of the Himalayas to the north (Fuloria 1993). Since then, subsidence and sedimentation in the onshore and offshore Mahanadi Basin areas has continued almost uninterrupted, although there have been significant fluctuations in the rate of sedimentation.

A stratigraphic breakdown of some of the wells in the Mahanadi basin is given in Fuloria (1993).

Hydrocarbons

Recently there have been potentially significant gas discoveries in the Upper Miocene offshore NE of the Mahanadi Basin, see http://www.dghindia.org/site/pdfattachments/e_p_reports_2005_06.pdf.

Reservoir rocks and seals

Good reservoir rocks exist in the Miocene and older sediments of the offshore shelf zone of the basin. Palaeogene sandstones have good porosities and permeabilities, and some of the carbonates have porosities of about 15%.

As most of the Miocene section is composed of claystones, potentially it could be a good regional cap-rock for hydrocarbon accumulation and CO_2 storage.

Good Early Cretaceous sandstone reservoir rocks are present in parts of the onshore basin, with porosities ranging from 15-25%. These reservoirs are effectively capped by both the Mio-Pliocene section and by the upper part of the Early Cretaceous section (Fuloria 1993) and so may have CO_2 storage potential.

Summary of CO_2 Storage Potential

Good potential probably exists in offshore as shown by the recent gas discoveries on the NE boundary of the basin, where it adjoins the Bengal Basin. The onshore basin could have some CO_2 storage potential, but the lack of hydrocarbon discoveries means that the potential in this area is classified as only fair.

References

Fuloria, R.C. 1993. 'Geology and Hydrocarbon Prospects of Mahanadi Basin, India.' In: Biswas, S.K., Dave, A, Garg, P., Pandey, J, Maithani, A., Thomas, N. J. (eds.), *Proceedings of the Second Seminar on Petroliferous Basins of India,* Vol.1, Indian Petroleum Publishers, Dehra Dun, India, pp. 355-370.

THE MUMBAI BASIN

Introduction

The Mumbai Basin (Figure A3.30) is a Cenozoic sedimentary basin located off the west coast of India. It covers an area of around 120,000 km^2 up to the 200 m isobath, beyond which there has not yet been any drilling (Ministry of Petroleum and Natural Gas 1991). It lies beneath the widest part of the Indian continental shelf (at around 300 km), which narrows to the north and south to around 60 km (Mitra et al., 1983).

It contains the giant Bombay High oil field and numerous smaller fields.

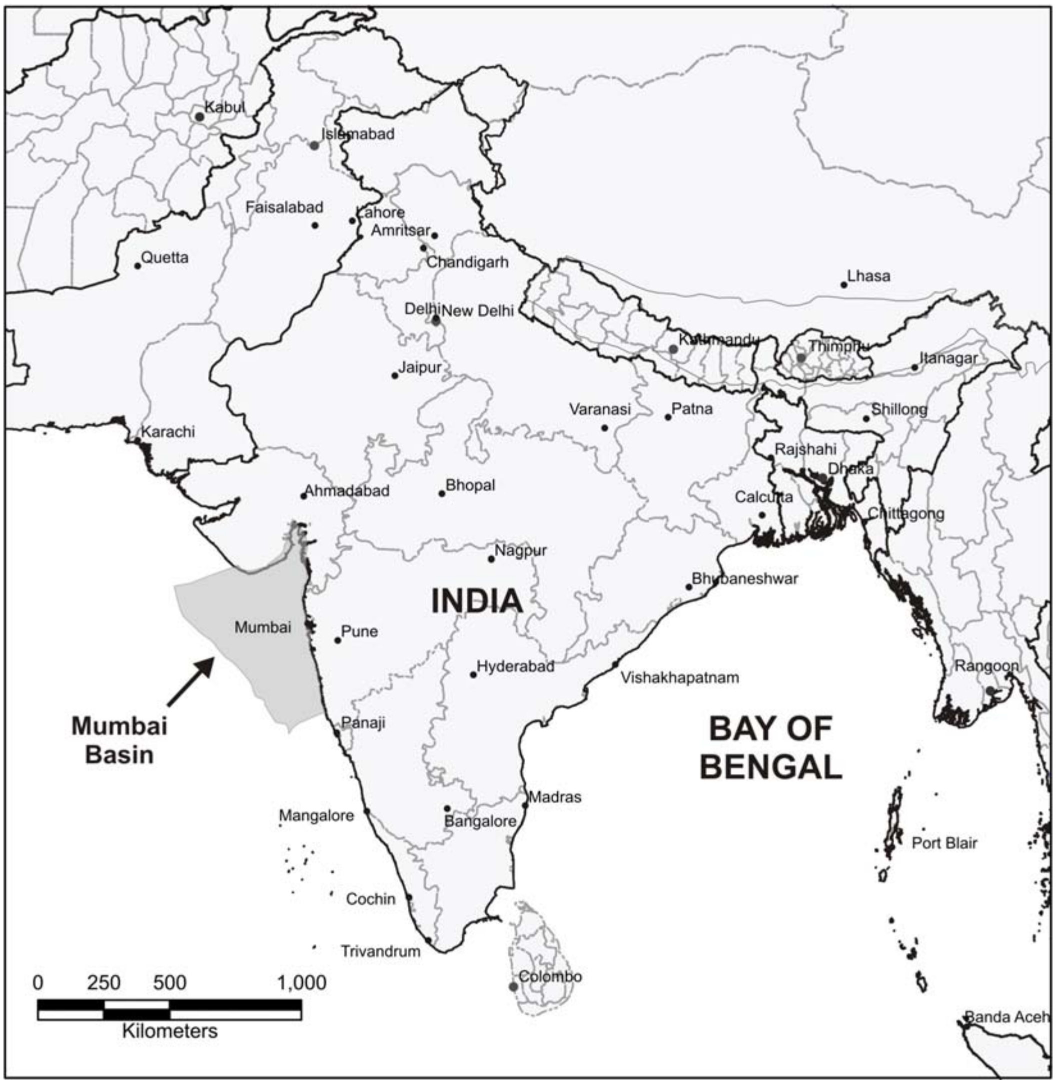


Figure A3.0 Location of the Mumbai Basin

The basin is bounded to the east by the coastal outcrops of the Deccan Traps and to the north by the Saurashtra Basin. Its southern limit is marked by the Vengural arch which separates it from the Konkan-Kerala basin (Ministry of Petroleum and Natural Gas 1991).

Structure

The thickness of Cenozoic sedimentary rocks offshore is around 1800-2000 m on the Bombay High and exceeds 5000 m in the deepest parts of the Surat Depression (Bhandari & Jain 1984).

Basin development was initiated by fault movement during the latest Upper Cretaceous or early Palaeocene (Sahay 1984). Two major structural episodes have been identified, the first resulting in the development of NNW-SSE-trending structures and the second in later east-west structures (Sahay 1984).

The Bombay High oilfield is a NNW to SSE-trending, doubly plunging anticline with a faulted eastern limb. The anticline is about 65 km long, 23 km wide and covers an area of about 1500 km^2 (Rao & Talukdar 1980).

Stratigraphy

The stratigraphy of the Mumbai Basin is summarised in Figure A3.31.

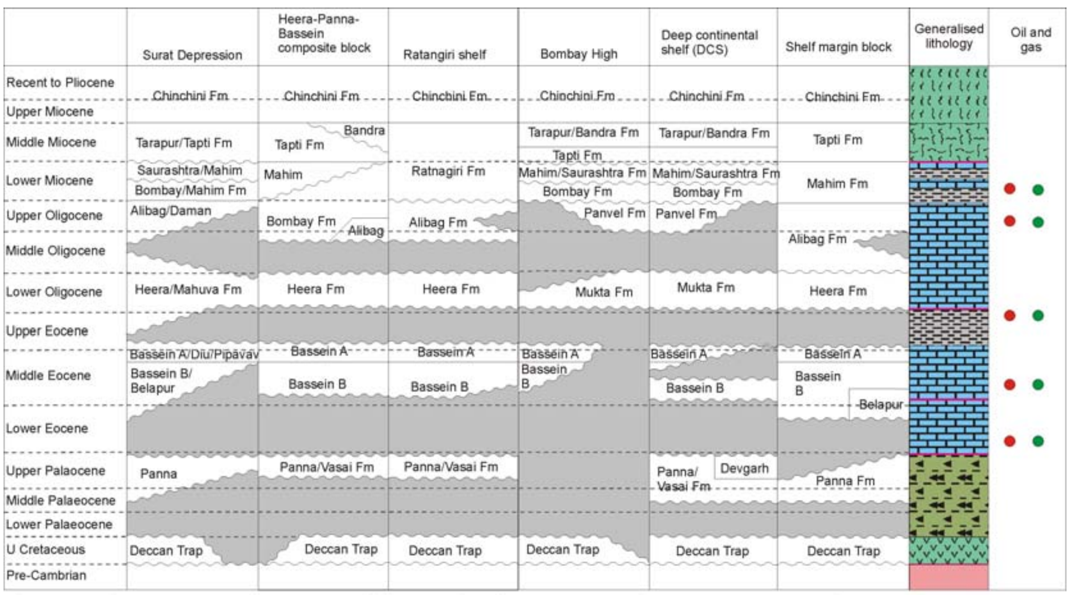


Figure A3.31 Summary stratigraphy of the Mumbai Basin (adapted from Mathur & Nair 1993, Basu et al. 1982 and Biswas 1993)

Generally, Cenozoic sedimentary rocks rest on Deccan Trap basalts, which were probably erupted over a limited period across the Cretaceous-Tertiary boundary, from about 63-66 Ma (Rathore et al. 1997). However, beneath parts of the Bombay High field the basement is formed by Precambrian quartzite, granitic gneiss and schist, and the Deccan Trap is absent.

The oldest Cenozoic strata are Palaeocene to early Eocene basal clastics (Panna, and Vasai formations). These are unconformably overlain by thick middle Eocene limestones (the Bassein Formation). The Bassein Formation was deposited basinwide with the exception of the part of the Bombay High. It is overlain by Upper Eocene to early Oligocene marine limestones with thin shale intervals (the Heera/Mahuva and Mukta formations) and, in the Surat Depression only, by deltaic Oligocene sands and shales (Mathur & Nair, 1993).

Unconformably deposited on these strata is a thick Early to Middle Miocene limestone and shale sequence. The Alibag and Saurashtra Formations are mainly shale with minor limestones, the Ratnagiri Formation is mainly limestone. These formations are followed, often unconformably, by upper Miocene to Pliocene claystones and shales (Tapti/Taraupur/Bandra Formations) (Sahay 1984, Basu et al. 1982).

Hydrocarbons

The Mumbai Basin produced over 60% of the total crude production in India in 1991, the vast majority of which came from the Bombay High field. The Bombay High field is reported to have ultimately recoverable reserves of 4 billion barrels of oil and 7.4 tcf gas according to http://www.hubbertpeak.com/laherrere/GPPI200701.pdf.

Reservoir rocks

In the Bombay High field, oil is produced from lower-middle Miocene limestones and the Bassein Formation (Ministry of Petroleum and Natural Gas 1991, Mitra et al. 1983).

Smaller reservoir intervals are also found in the Middle Miocene L-II carbonate, the S-1 (sandstone) gas pay, and, in the Bombay High, Bombay High East, Ratna and B-57 hydrocarbon fields, the Palaeocene to Lower Eocene basal sand horizon (Mitra et al. 1983). The basal sand sequence is composed of Deccan Trap wash, fluvio-deltaic sand, shale, silt alternating with local marine tongues in the Ratnagiri and south Saurashtra area. Deposition appears to have been fault-controlled (Mitra et al. 1983). Thickness varies from 0-2400 m across the basin (Mishra et al. 1997).

Cap rocks

Post-Miocene shales are expected to form an effective caprock over the entire basin except for the Ratnagiri block, where they are absent (Rao & Talukdar 1980).

Mumbai High Field

The Bombay High field is divided into three main blocks by NE to ENE-WSW-trending faults. The three blocks have oil-water contacts at different depths. All the blocks have a gas cap. The gas cap is at the same depth in the middle and southern blocks (Rao & Talukdar 1980), which therefore probably have a degree of connectivity. The northern block is believed to contain more than half the oil reserves of the entire Mumbai Basin (Rao & Talukdar 1980).

The Bombay High reservoirs are the L-III (Early Miocene), L-II (Middle Miocene), S-1 gas sands (Middle Miocene) and Palaeocene to Early Eocene basal sands (Mitra et al., 1983). The top of the youngest reservoir (L-II) is at around 1100 m.

The top of the main reservoir, L-III is at around 1400 m (Roychoudhury & Deshpande, 1982; Biswas, 1993). It consists of fine-grained bioclastic limestone. It has largely secondary porosity of 0-25% (Roychouldhury & Deshpande, 1982).

Hardas et al. (1989) studied samples of the Panna Formation sandstones (Palaeocene-Early Eocene age) which are a secondary reservoir. They consist of coarse-fine grained and poorly sorted sands with authigenic cements. They can have good primary porosity where it has not been destroyed during diagenesis and good secondary porosity due to dissolution of primary and authigenic minerals, removal of matrix and cement and minor fractures.

Overpressure

High pressures occur in the deeper parts of the Mumbai Basin. They are encountered in Palaeogene to Early Miocene strata in the Saurashtra area, Palaeogene to Early Oligocene strata in the Daman-Tapti area and Palaeocene to Eocene strata in the central graben area (Porwal et al., 1994). They are believed to result from undercompaction due to high sedimentation rates.

CO_2 storage potential

The majority of reservoirs in this region are carbonates, so CO_2/water/rock reactions may be important. Many, such as those in the Bassein area, are deeply buried, e.g. the top reservoir horizon was encountered at 2295 m in well Bassein-1 (Roychoudhury & Deshpande, 1982). Porosity is variable, commonly ranging from 0-30% in an individual formation. Primary porosity is often only a few percent and secondary porosity is more important (Roychoudhury & Deshpande, 1982).

The post-Miocene shales form a regional cap rock over the whole Mumbai Offshore, except for the Ratnagiri Block.

The Mumbai offshore is a huge area which appears to have good potential for CO_2 storage. However, more detailed study is required to determine the most favourable sites: reservoir porosity variation in particular should be considered. Areas of overpressure may have to be avoided if CO_2 injection would raise the reservoir pore fluid pressure above acceptable limits.

References

Basu, D.N, Banerjee, A. & Tamhane, D.M. 1982. Facies distribution and petroleum geology of the Bombay offshore basin, India. *Journal Petroleum Geology*, **5**(1), pp51-75

Bhandari, L.L. & Jain, S.K. 1984. Reservoir geology and its role in the development of the L-III reservoir, Bombay High field, India. *Journal of Petroleum Geology*, **7**(1), 27-46.

Biswas, S. K. 1987. Regional tectonic framework, structure and evolution of the western marginal basins of India. *Tectonophysics,* **135**, 307-327.

Biswas, S.K. 1993. Geology of Bombay offshore shelf and hydrocarbon occurrences. *Indian Journal of Geology*, **65**(4), 215-245.

Hardas, M.G., Sharma, S. & Das, K.K. 1989. Diagenesis and secondary porosity: a preliminary appraisal of Tertiary sandstones from Indian sedimentary basins. *Bulletin ONGC*, **26**(1), 31-52.

Mathur, R.B. & Nair, K.M. 1993. Exploration of Bombay offshore basin. In: Biswas, S.K., Dave, A, Garg, P., Pandey, J, Maithani, A., Thomas, N. J. (editors), *Proceedings Second Seminar on Petroliferous basins of India,* Vol 2, Indian Petroleum Publishers, Dehra Dun, India, pp365-396.

Ministry of Petroleum and Natural Gas 1991. India: Opportunities for oil and natural gas exploration. Ministry of Petroleum and Natural Gas, Government of India.

Mishra, Y.K., Parida, G. & Ramani, K.K.V. 1997. Stratigraphic-depositional model: an important tool for stratigraphic trap exploration of basal clastic unit in Bombay offshore basin. *Proceedings Second International Petroleum Conference and Exhibition PETROTECH-97, New Delhi*, pp. 463-474.

Mitra, P., Zutshi, P.L., Chourasia, R.A., Chugh, M.L., Ananthanarayanan, S. & Shukla, B. 1983. Exploration in western offshore basins. In: L.L. Bhandari, B.S. Venatachala, R. Kumar, S.N. Swamy, P. Garga & D.C. Srinastava (editors), *Petroliferous basins of India*. Petroleum Asia Journal, November 1983, pp15-24.

Mitra, D.S., Bhoi, R. & Agarwal, R.P. 1993. Hydrocarbon exploration in Shargarh and Myajlar subbasins of Jaisalmer Basin, Rajasthan, India using remote sensing techniques. *Indian Journal Petroleum Geology,* **2**(1), 31-42.

Ministry of Petroleum and Natural Gas 1991. India: Opportunities for oil and natural gas exploration. Ministry of Petroleum and Natural Gas, Government of India.

Rao, R.P. & Talukdar, S.N. 1980. Petroleum geology Bombay and high field, India. In: M T Halbouty (editor) Giant oil and gas fields of the decade 1968-1978. *American Association Petroleum Geologists' Memoir*, **30**, 487-506.

Rathore, S.S. , Vijan, A.R., Prabhu, B.N. & Misra, K.N.K. 1997. Ar-dating of basement rocks of Bombay Offshore basin. *Proceedings Second International Petroleum Conference and Exhibition PETROTECH-97, New Delhi*, pp583-588.

Roychoudhury, S.C. & Deshpande, S.V. 1982. Regional distribution of carbonate facies, Bombay Offshore Region, India. *Bulletin American Association of Petroleum Geologists,* **66**(10), 1483-1496.

Sahay, B. 1984. A review of the geology and petroleum possibilities of the continental margins of India. *Offshore Technology conference 4699, 16th conference May 1984*, pp 451-464.

THE NARMADA BASIN

Introduction

The Narmada graben is an ENE-WSW trending depression in the northwest of India. It is bounded by a series of sub-parallel wrench faults that define the Narmada-Son lineament (or geofracture). This is a deep fracture that extends into the Moho at a depth of 35-40 km (Biswas 1987, Kaila et al. 1981, 1985). The Narmada basin (Figure A3.32) is largely confined to the narrow ENE-WSW trending Narmada graben, which is bounded to the north and south by faults, though it opens out at its western end (Biswas & Deshpande 1983).

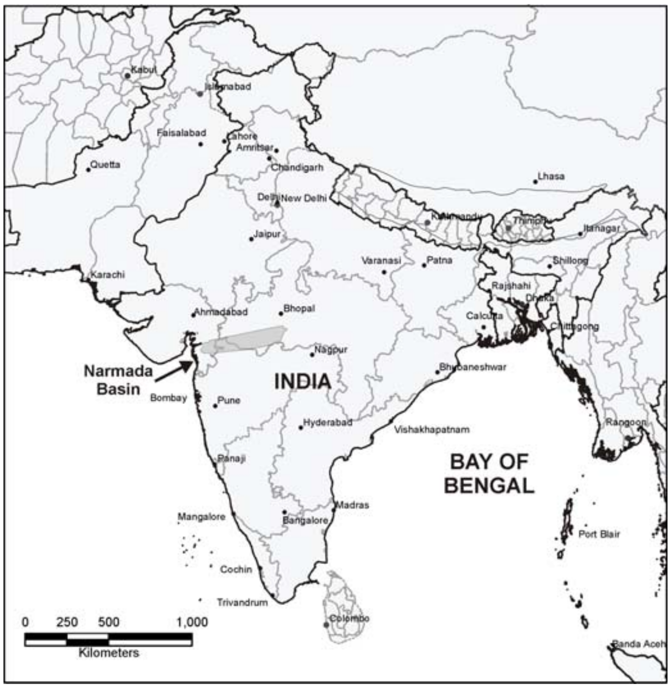


Figure A3.32 Location of the Narmada Basin

Structure

The major part of the basin lies in a graben along the course of the Narmada-Son lineament. The Narmada-Son lineament forms a tectonic boundary between the shallow marine Late Proterozoic-Palaeozoic Vindhyan strata in the north and transitional Gondwana deposits in the south (Kaila et al. 1981, 1985). This region of India has a complex tectonic history of reactivation of Pre-Cambrian structure. During Early Cretaceous times, reactivation resulted in rifting along the Narmada geofracture with the opening of a basin at its western end (Kaila et al. 1981, 1985; Biswas, 1987). The Narmada rift further opened and received marine sediments during the Late Cretaceous (Biswas 1987). Uplift of the Saurashtra arch to the northwest of the Narmada basin appears to have terminated Cretaceous sedimentation (Biswas 1987).

Deccan Trap basalts of late Cretaceous-early Cenozoic age overlie the Cretaceous sediments. A Cenozoic depocentre (Broach sub-depression) formed where the Narmada rift intersects the Cambay rift (Kaila et al. 1981, Biswas 1987).

Stratigraphy

Cretaceous subsidence in the Narmada basin was restricted to the western part of the rift zone within an embayment widening and deepening towards the west. Maximum subsidence of the basin before deposition of the Deccan Trap basalts was around 1700 m, centred where the central Narmada graben meets the Godavari graben (Biswas, 1987).

Cretaceous sediments were generally deposited directly on Precambrian basement (Figure A3.33). Early Cretaceous fluvio-deltaic deposits (over 1800 m) are present in the west part of Narmada basin (Biswas, 1987). The Lower Cretaceous Nimar Group consists of the rough cross-bedded fluvial Nimar sandstones (with some tabular cross-bedding and deltaic and marine influence in the west where the sandstone is also known as the Songir/Himmatnagar Group) followed by the Uchad/Umrali flagstone in the central and western parts of the basin (Biswas & Deshpande, 1983). The Nimar group gradually thickens towards the west from around 15-30 m to over 150 m (Biswas & Deshpande, 1983). Fluvial fans either side of the graben in the Early Cretaceous contributed to the Nimar Group. The Himmatnagar sandstone appears to indicate the basin opened out to the west (Biswas & Deshpande, 1983).

The Bagh Group (Navagam in western part) consist of nodular limestone (argillaceous, thin bedded becoming less nodular and more shaly westwards), followed by coralline limestone (thick bedded, hard, crystalline, fossiliferous and coarse grained, followed by the Lameta Formation (thick bedded limestone, variable grain size, typically cherty) (Biswas & Deshpande, 1983). The nodular limestones represent the greatest sea depth and the following higher energy environment Coralline limestone represents regression of the sea to intertidal conditions. Further regression resulted in increased clastic input to the Lameta Formation (Biswas & Deshpande, 1983). Part of the Lameta limestone appears to have been deposited where the basin opened out westwards (Biswas & Deshpande, 1983).

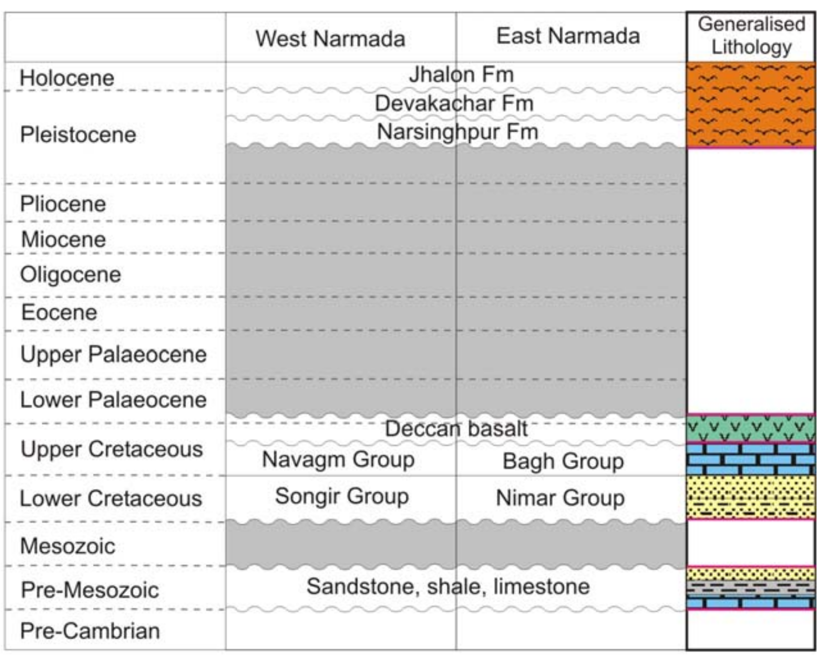


Figure A3.33 Stratigraphic summary for the Narmada Basin (after Biswas & Deshpande 1982, Ganjoo 1995, Biswas 1987, Mitra et al. 1983)

Hydrocarbons

No hydrocarbons have yet been found in the Narmada Basin.

CO_2 storage potential

In the Narmada basin, over 900 m Deccan Trap covers thin Cretaceous sediments deposited unconformably on pre-Mesozoic sands and igneous basement (Biswas, 1987). The Bagh Formation could potentially store CO_2, below the Deccan Trap basalt. However the necessity of drilling through the large thickness of the Deccan Trap may well make the Narmada Basin unfavourable for CO_2 storage and at present its potential is considered limited.

References

Biswas, S. K. 1987. Regional tectonic framework, structure and evolution of the western marginal basins of India. *Tectonophysics,* **135**, 307-327.

Biswas, S.K. & Deshpande, S.V. 1983. Geology and hydrocarbon prospects of Kutch, Saurashtra and Narmada basins. In: L.L. Bhandari, B.S. Venatachala, R. Kumar, S.N. Swamy, P. Garga & D C Srinastava (editors), *Petroliferous basins of India*. Petroleum Asia Journal, November 1983, 111-126.

Kaila, K.L., Krishna, V.G. & Mall, D.M. 1981. Crustal structure along Mehmadabad-Billimora profile in the Cambay basin, India, from deep seismic soundings. *Tectonophysics,* **76**, 99-130.

Kaila, K.L., Reddy, P.R., Dixit, M.M., & Koteswara Rao, P. 1985. Crustal structure across the Narmada-Son lineaments, central India, from deep seismic soundings. *Journal Geological Society India*, **26**(7), 465-486.

THE POTWAR BASIN

The Potwar Basin, sometimes known as the Kohat-Potwar or Upper Indus Basin, covers an area of about 40,000 km^2. It is bounded to the north and west by the Main Boundary Thrust – the southernmost of the major Himalayan thrusts. It is separated from the Lower Indus Basin to the south by the Salt Range and Sargodha High. It is bounded to the west by the Kurram Fault and to the east by the Jhelum Fault (Kadri 1995, Wandrey et al. 2004).

A map showing the locations of the 18 oil and 3 gas fields in the basin is given in Wandrey et al. 2004, Figure 13). Production started in 1914 from the Khaur field. Oil and gas production occurs from a stratigraphically wide range of reservoirs. A summary of the characteristics of the reservoirs in the basin is given in Kadri (1995). Reservoir rocks include Miocene alluvial sandstones, Paleogene shelf carbonates, Jurassic and Permian continental sandstones, and Cambrian alluvial and shoreface sandstones. Approximately 60% of the reservoirs are carbonates, in which production may be largely from fractures. The sandstone reservoirs have porosities ranging from 5 to 30%, averaging between 12 and 16%. Sandstone reservoir permeability ranges from 1 to >300 mD and averages 4 to 17 mD (Wandrey et al. 2004).

CO_2 storage potential

The better sandstone oil and gas reservoirs are likely to have some potential for CO_2 storage. Seals include fault truncations and interbedded shales and the thick shales and clays of the Miocene and Pliocene Siwalik Group. In terms of aquifers, the Siwalik Group sandstone reservoirs may have significant storage potential, as should the aquifer portions of the better oil and gas field reservoir sandstones. Consequently the basin is classified as having good CO_2 storage potential.

References

Kadri, I.B. 1995. *Petroleum Geology of Pakistan*. Pakistan Petroleum Ltd, Karachi, 275 pp.

Khan, M.A., Ahmed, R., Raza, H.A., and Kemal, A., 1986, Geology of petroleum in Kohat-Potwar Depression, Pakistan: *American Association of Petroleum Geologists Bulletin*, **70** (4), 396 – 414.

Wandrey, C.J., Law, B.E. & Shah, S.H.A., 2004. Patala-Nammal Composite Total Petroleum System, Kohat-Potwar Geologic Province, Pakistan. In: Wandrey, C.J. (ed.), *Petroleum Systems and Related Geologic Studies in Region 8, South Asia.* USGS, 1-19.

THE PUNJAB SHELF

Introduction

Evidence from wells and seismic surveys indicates that the basement surface beneath the Cainozoic strata of the Punjab Shelf dips gently northwards to a depth of at least 4.5 km adjacent in the region of Dasuya in the Himalayan foothills.

Wells

The southern Zira well near Ferozepur proved an approximate 700 m thick Upper and Middle Siwalik succession beneath which it encountered granitic basement rocks (Rao, 1973; Parkash & Kumar, 1991).

The Adampur well near Jullander proved the presence of Lower Siwalik sediments before entering basement at a depth of 2513 m.

The Hashairpur well, drilled to a depth of 3439 m, proved Upper and Middle Siwalik sediments before reaching TD in the Lower Siwalik Group as a result of drilling difficulties (Rao, 1973; Parkash & Kumar, 1991).

The Adampur and Hoshairpur wells may be located on NW-SE trending shallow highs in the basement that die out to the NW around Gurudaspur (Rao, 1973).

North-eastwards from Dasuya, the basement surface continues to deepen and Cenozoic sediments thicken, as indicated by the Janauri #1 and #2 wells (the latter drilled to over 5 km), which tested the Januari Anticline in the foothills (Rao, 1973). A thick section of Siwalik Group sediments was proved (4790 m) beneath which marble assigned to the basement was encountered.

Folding of the sequence becomes more apparent to the NE up to the Main Boundary Thrust, with the Jawalamukhi and Bahl wells reaching TD before reaching basement (Rao, 1973).

Within the Punjab Shelf, several ridges and depressions are recognised, including:

The Aravalli Horst – extends from Roopnagar on Sutlej to the Sarda River in the SE.

The Dudwa Ridge – E-W trending ridge close to the foothills of Nepal.

CO_2 storage potential

The Punjab Shelf is considered to have low CO_2 storage potential for the same reasons as the Ganga Basin. It appears to lack consistently developed cap rocks and its aquifers support a dense population heavily reliant on agriculture. Therefore there are likely to be serious conflicts of interest with any proposed CO_2 storage.

References

Parkash, B. & Kumar, S. 1991. The Indogangetic Basin. In: Tandon, S.K., Pant, C.C. & Casshyap, S.M. (editors), *Sedimentary basins of India: Tectonic Context*. Gyanodaya Prakashan, Nainital, India, pp. 147-170.

Rao, 1973. The subsurface geology of the Indogangetic Plains. *Journal Geological Society India*, **14**, 217-242.

THE RAJMAHAL BASIN

The Rajmahal Basin is a Gondwana Basin lying immediately to the west of the Rajmahal Traps in northern peninsula India. The Gondwana strata, which include the Permian coal-bearing Barakar Formation, may be present beneath the Rajmahal Trap and are at least patchily developed beneath the western margin of the Bengal Basin. It is possible that they could have some CO_2 storage potential beneath the trap but this is far from proven and consequently the basin is classified as have limited potential at present.

References

Mondal, A. 2006. Gondwana Basins in India – Vast Geologic Storage Sites for CO_2 Injection. *Proceedings of the International Workshop on R&D Challenges in Carbon Capture & Storage Technology for Sustainable Energy Future (IWCCS-07)*, 12-13 January 2007. National Geophysical Research Institute, Hyderabad.

THE REWA BASIN

The Rewa Basin (Figure A3.35) is a Gondwana basin in which sedimentary rocks of Permian-Cretaceous age were deposited on metamorphic basement.

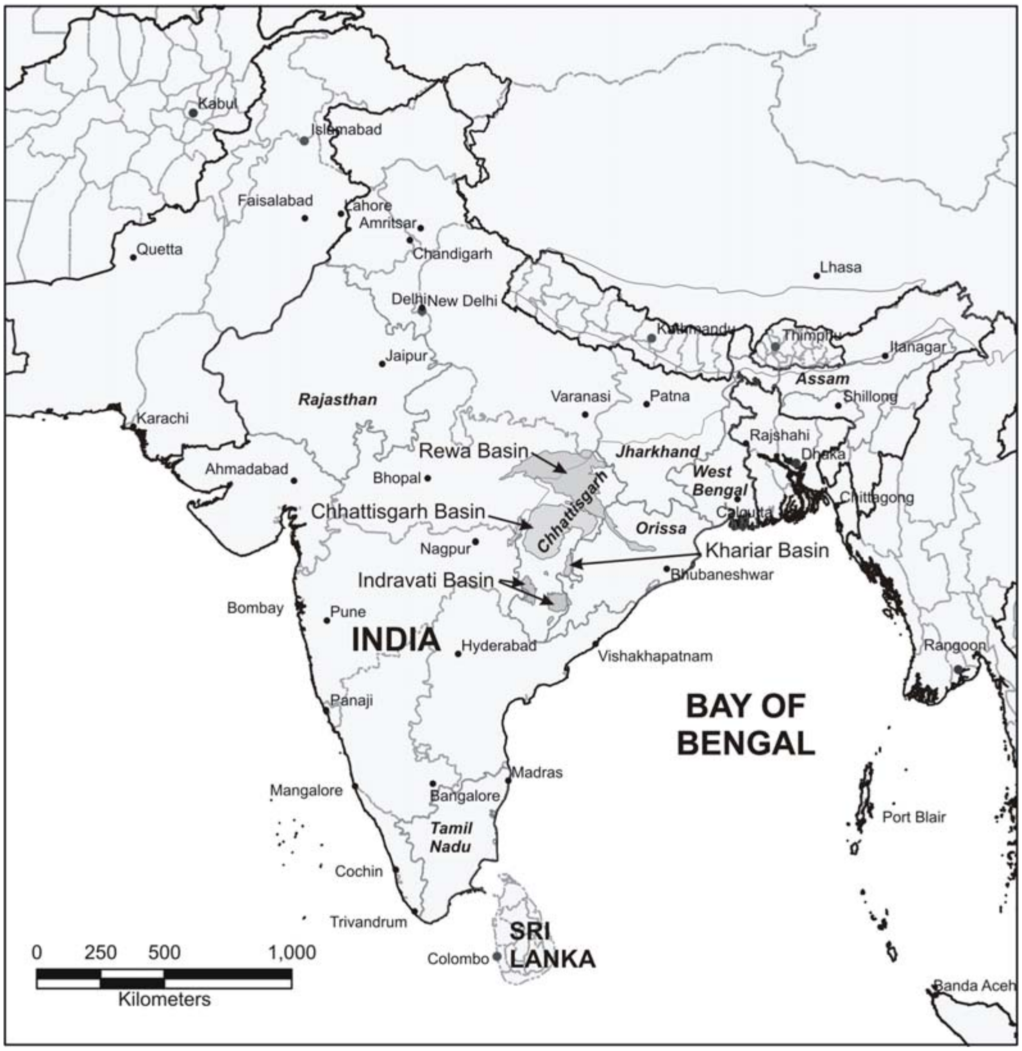


Figure A3.35 Location of the South Rewa Basin

Structure

The Rewa Gondwana basin lies at the northern end of the Son-Mahanadi Graben, which is orientated NNW-SSE, approximately parallel to the Pranhita-Godavari graben, following one of the major Indian Precambrian structural trends (Ghosh 2002). Up to 3.8 km of sedimentary rocks are present in the basin centre (Mondal 2007).

Stratigraphy

The stratigraphic succession (Figure A3.36) is similar to that in the Damodar Valley Gondwana Basins (e.g. Dutta 2002, Shah 2004). However, unlike Damodar Valley or Satpura Basin, the Gondwana sequence of the Rewa Basin is dominated by arenaceous facies. The shale-dominated lower part of the Barren Measures, although locally attaining a thickness of around 100m, is not regionally persistent and hence it can not be considered as cap rock over a large area. Likewise, clay dominated Tiki Formation also has a restricted occurrence in the north-western part of the basin (Mondal 2007.

AGE	LITHOLOGY	FORMATION /GROUP		THICKNESS (M)
HOLOCENE	CONGLOMERATES AND GRAVEL	ALLUVIUM		
JURASSIC	CONGLOMERATE, SHALE, COARSE FERRUGINOUS SANDSTONE	PARSORA FORMATION (EQUIVALENT TO MAHEDEVA)		800
TRIASSIC	SANDSTONE AND SHALE	PALI-TIKI FORMATION (EQUIVALENT TO PANCHET)		1300
UPPER PERMIAN	SANDSTONE, SILTSTONE, CLAY, COAL SEAMS	DAMUDA GROUP	RANIGANJ FORMATION	700-900
LOWER PERMIAN	SHALE, FINE-COARSE SANDSTONE, SHALE WITH IRONSTONE NODULES		BARREN MEASURES FORMATION	100-500+
	SANDSTONE AND SHALES		BARAKAR FORMATION	700-1100
	SANDSTONE AND SHALES	TALCHIR FORMATION		<100-120
PRE-CAMB	ARCHEAN GRANITES AND METASEDIMENTS (BASEMENT COMPLEX)			

Figure A3.36 South Rewa Basin stratigraphy, after Singh et al., (2007) and Dutta (2002)

Hydrocarbons

No oil or gas fields or shows have been found in the South Rewa basin.

CO_2 Storage Potential

The Coal Measures found on the southern margin of the basin dip towards the basin centre and are buried to significant depths in the basin centre. However, in the absence of suitable cap rocks, this basin is unlikely to provide storage sites, in spite of the presence of reservoir rock over a large area. Consequently it has been classified as having little potential at present.

References

Dutta, P. 2002 Gondwana lithostratigraphy of Peninsular India. *Gondwana Research* (Gondwana Newsletter Section) **5** (2), 540-553.

Mondal, A. 2006. Gondwana Basins in India – Vast Geologic Storage Sites for CO_2 Injection. *Proceedings of the International Workshop on R&D Challenges in Carbon Capture &*

Storage Technology for Sustainable Energy Future (IWCCS-07), 12-13 January 2007. National Geophysical Research Institute, Hyderabad.

Singh, K. J., Goswami, S. and Chandra, S. 2007 Occurrence of cordialities from Lower Gondwana sediments of Ib-River coalfield, Orissa, India: An Indian scenario. *Journal of Asian Earth Sciences,* **29**, 666-684

THE SAURASHTRA BASIN

Introduction

The Saurashtra Basin (Figure A3.37) is a Mesozoic rift basin on the western margin of the Indian Craton on the west coast of India. It covers an area of around 28000 km^2 (Sahay 1984, Biswas 1987).

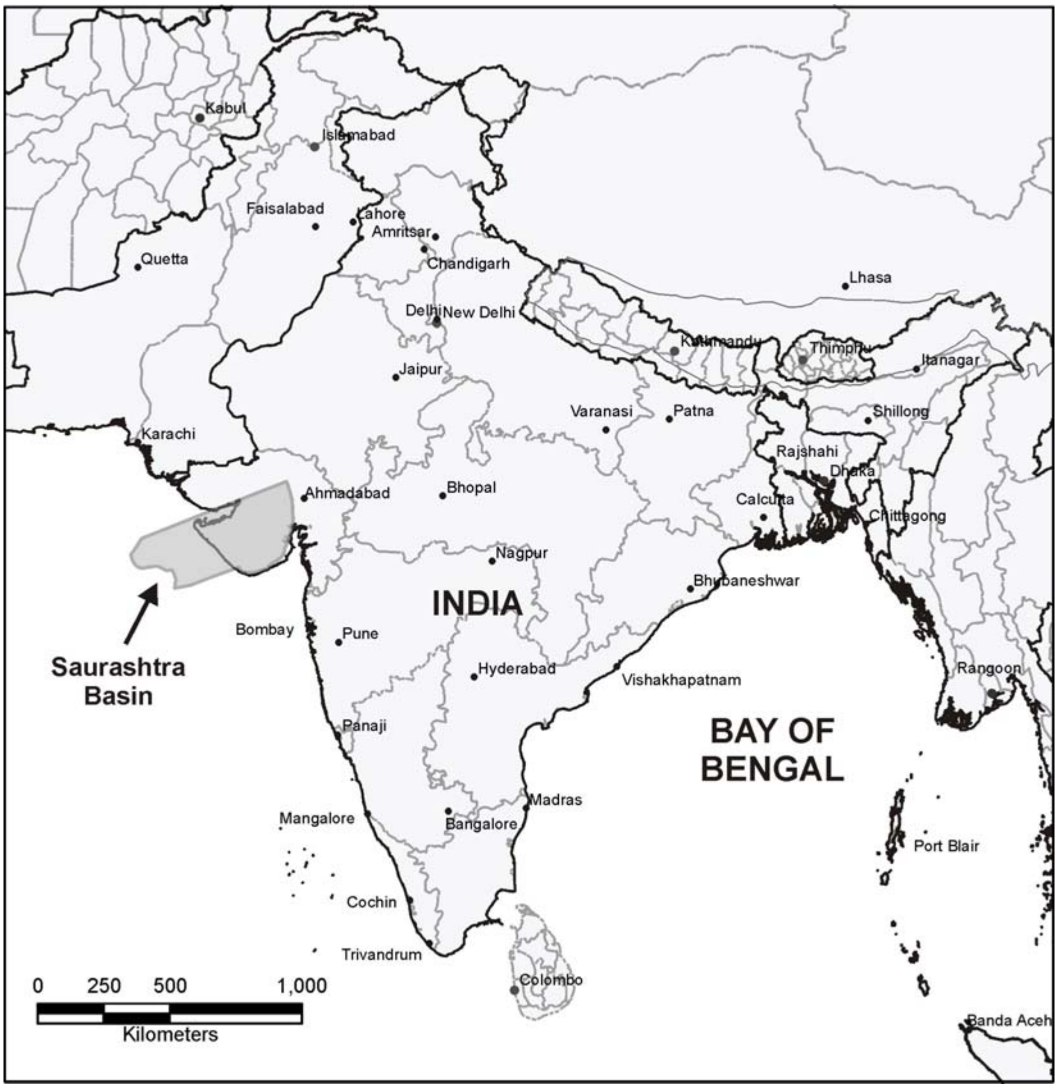


Figure A3.37 Location of the Saurashtra Basin

The Saurashtra Basin is bounded to the north by the Kutch Basin, to the east by the Cambay Basin and to the south by the Surat depression (part of the Mumbai Shelf). To the west it opens out into the Arabian Sea (Biswas & Deshpande 1983).

Structure

The entire area forms a horst block, on which Lower Cretaceous sedimentary rocks are overlain by Deccan Trap basalts and thin Neogene and Quaternary deposits. Deccan Trap basalts are at surface over most of the Saurashtra peninsula (Biswas & Deshpande 1983). Prominent structural 'noses' plunging to the NNE are identified in the Cenozoic rocks that overlie the Deccan Trap.

Stratigraphy

Cretaceous sediments on the Saurashtra arch are expected to have a thickness ranging from 2000m on the flanks to 1000m on the crest (Biswas & Deshpande, 1983). Deccan Trap basalt volcanics covered the Saurashtra basin during the Late Cretaceous. The Deccan Trap surface was peneplaned and the south and west coastal margins were covered with marine sediments of the Gaj and Dwaraka Formations during a Neogene transgression (Biswas & Deshpande, 1983).

During the Quaternary, shallow marine sediments were deposited on the coastal margins and subaerial sediments were deposited across the remainder of the basin (Biswas & Deshpande, 1983).

Hydrocarbons

Natural gas was encountered in a borehole drilled at Gogha in 1915 (Johri & Kandpal 1983). In the offshore western part of the Saurashtra arch, a closure in the lower Eocene potentially suitable for hydrocarbon generation and trapping, caused by an older structure has been identified. Other fault closures in the Lower/Middle Eocene have also been mapped (Mitra et al. 1983).

The Cenozoic is too thin to be of interest for hydrocarbon exploration onshore. However, based on the dip of the sediments, offshore Cenozoic thickness could be expected to be much greater (Biswas & Deshpande, 1983). A deep well drilled west of the continental margin encountered over 2000 m of Cenozoic sediments at 2530 m. Palaeocene sediments (which can be seen to pinch out shorewards in seismic sections) would be expected to consist largely of coarse carbonate reservoir or reefal facies deposited along the continental margin. The pinchout may form potential traps (Biswas & Deshpande, 1983).

CO_2 storage potential

There is little or no potential onshore but offshore where the sedimentary succession is thicker, there may be limited CO_2 storage potential in the Saurashtra Basin.

References

Biswas, S. K. 1987. Regional tectonic framework, structure and evolution of the western marginal basins of India. *Tectonophysics,* **135**, 307-327.

Biswas, S.K. & Deshpande, S.V. 1983. Geology and hydrocarbon prospects of Kutch, Saurashtra and Narmada basins. In: L.L. Bhandari, B.S. Venatachala, R. Kumar, S.N. Swamy, P. Garga & D C Srinastava (editors), *Petroliferous basins of India*. Petroleum Asia Journal, November 1983, 111-126.

Johri, D.N. & Kandpal, L.D. 1983. Exploration for oil and natural gas in Saurashtra plateau – a geophysical review. *Special Publication Geological Survey India*, **2**, 89-100.

Mitra, P., Zutshi, P.L., Chourasia, R.A., Chugh, M.L., Ananthanarayanan, S. & Shukla, B. 1983. Exploration in western offshore basins. In: L.L. Bhandari, B.S. Venatachala, R. Kumar, S.N. Swamy, P. Garga & D.C. Srinastava (editors), *Petroliferous basins of India*. Petroleum Asia Journal, November 1983, pp.15-24.

Sahay, B. 1984. A review of the geology and petroleum possibilities of the continental margins of India. *Offshore Technology Conference 4699, 16th May 1984*, pp 451-464

Singh, B.P., Khan, M.S.R., Goyal, J.P., Dwivedi, P., Sharma, A.K., Mittal, A.K. & Pande, A. 1997. Genetic correlation of biodegraded crude oils from Padra area of Broach-Jambusar block, Cambay basin, India using n-Alkane, biomarker and stable carbon isotopic compositions. *Proceedings Second International Petroleum Conference and Exhibition PETROTECH-97, New Delhi*, pp237-243.

THE SATPURA BASIN

The Satpura Basin is a Gondwana Basin that lies in the heart of peninsula India, along the Narmada-Son lineament. It covers an area of about 5000 km^2. It contains an early Permian to Triassic succession similar to that of the other Gondwana basins, but this is unconformably overlain by a Cretaceous succession comprising the Lower Cretaceous Jabalpur Formation, the Upper Cretaceous Lametas Formation and the latest Cretaceous to earliest Palaeocene Deccan Trap. The Pench-Kanhan-Tawa Valley coalfield lies on the southern margin of the basin. This is characterised by a high degree of structural disturbance and E-W faulting. The coalfield also shows evidence of intrusion by dykes associated with the Deccan Traps. The structure of the central part of the basin is less well known. The sandy parts of the Barakar Formation, along with the Bijori and Panchmari formations may provide suitable reservoirs, and the clay-dominated Motur and Denwa Formations could have sealing potential (Mondal 2007). However, until this potential can be firmed up, its CO_2 storage potential is classified here limited.

References

Mondal, A. 2006. Gondwana Basins in India – Vast Geologic Storage Sites for CO_2 Injection. *Proceedings of the International Workshop on R&D Challenges in Carbon Capture & Storage Technology for Sustainable Energy Future (IWCCS-07)*, 12-13 January 2007. National Geophysical Research Institute, Hyderabad.

THE VINDHYAN BASIN

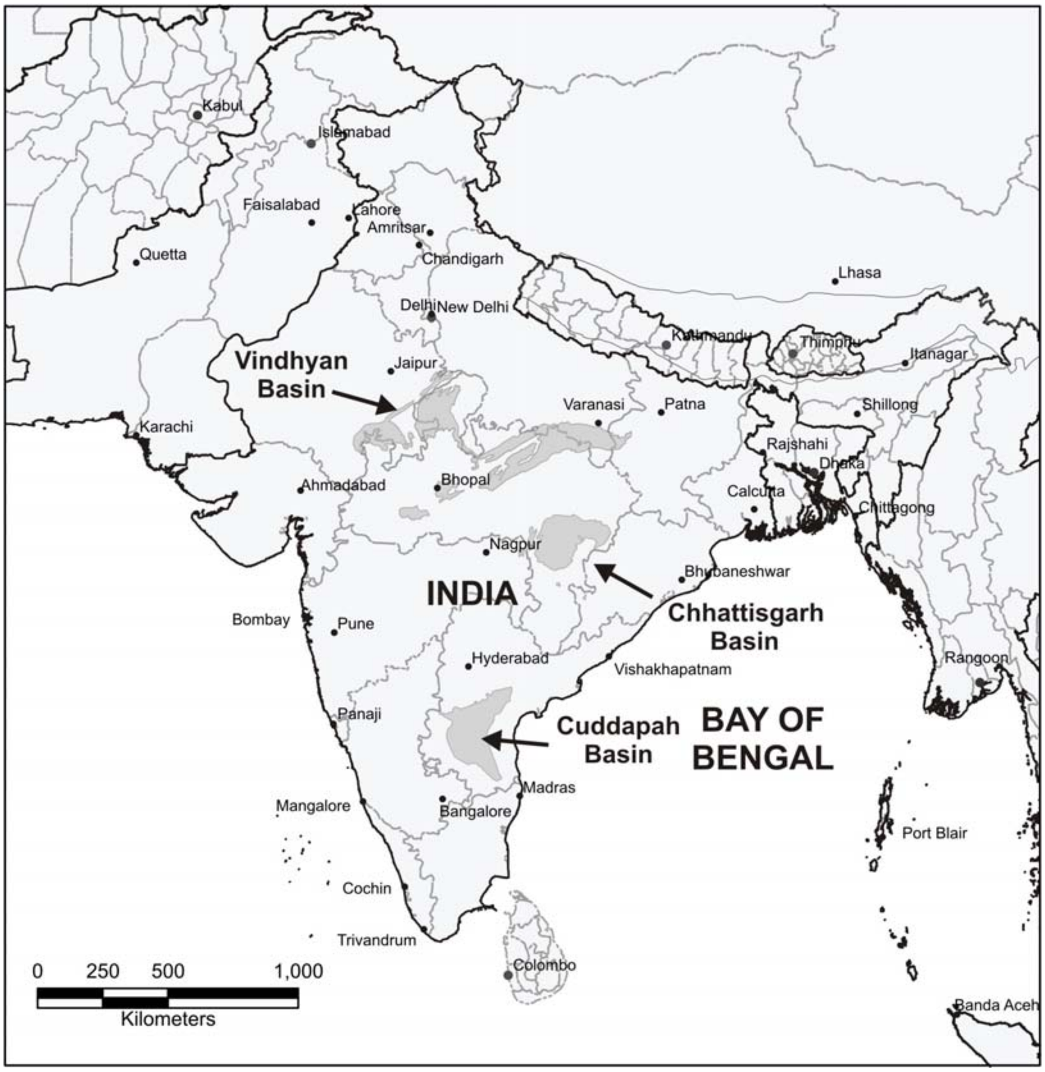


Figure A3.38 Location of the major Proterozoic basins of India

Introduction

The Vindhyan Basin (outcropping parts of which are shown in Figures A3.38 and A3.39) is a large intra-cratonic Proterozoic basin on the northern part of the Indian Shield. It covers an area of about 166400 km^2. About 40,000 km^2 of the northern part of the basin is concealed beneath Ganges river alluvium and Cenozoic sedimentary rocks. On the basis of geophysical evidence the basin is thought to extend up to (and thus possibly beneath) the frontal thrust of the Himalayas. The southern and south-western parts of the basin are covered by the Deccan Traps. Concealed Vindhyan strata are present as far west as the Moradabad Fault and as far east as the Patna Fault (Figure A3.39).

The exposed Bundelkhand Massif (of Archaean age), and its subsurface continuation the Faizabad Ridge, lie in the centre of the basin. They trend roughly northeast-southwest and divide the basin into two parts, one lying within the Chambal Valley to the west and the other lying in the Son Valley to the east. They influenced sedimentation during deposition of the basin fill.

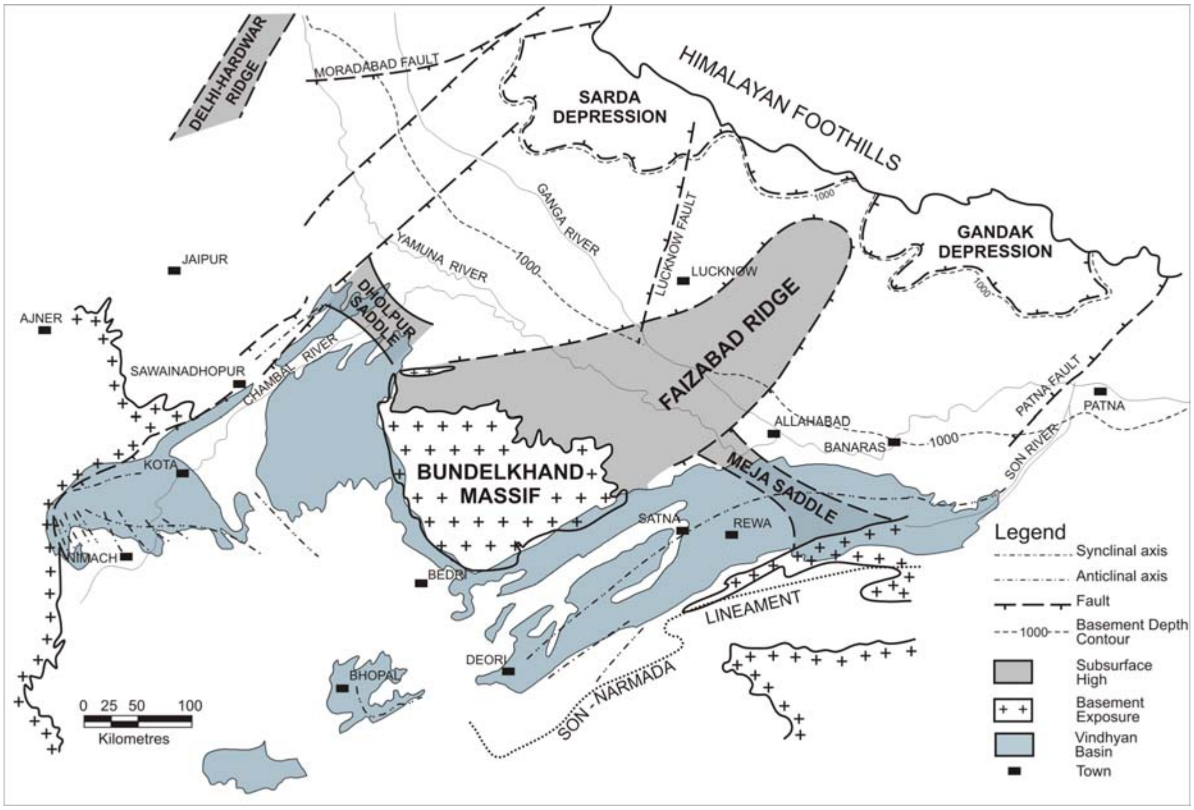


Figure A3.39 Location map of Vindhyan Basin

Stratigraphy

The basin is of Proterozoic age. Its fill is thought to span the time interval from 1400 Ma to 500 Ma (Prasad & Verma 1991).

The sedimentary rocks that fill the Vindhyan Basin are known as the Vindhyan Supergroup. They are stratified, unmetamorphosed sandstones and shales, with subordinate limestones. They attain a maximum thickness of about 5250 m.

Potential reservoir rocks

No detailed studies of the reservoir properties of the Vindhyan rocks have been made. However, Aswathi (quoted in Srivastava et al.1983) concludes that the interval velocity of the Vindhyan sediments beneath the Ganges plain indicates extremely poor reservoir properties. Peters, Bhatnagar & Singh (1997) also state that Vindhyan sediments have poor primary porosity.

Potential cap rocks

Good shale sequences are present that, if not heavily fractured, might seal any reservoir horizons, especially in the Upper Vindhyan Group.

Structure

There are some apparently suitable structures for CO_2 storage in the basin, e.g. along the south-eastern boundary of the Bundelkhar Massif, and along the Narmada-Son Lineament, where many anticlinal structures are present in a linear belt.

Summary of carbon dioxide storage potential

The absence of recorded good quality reservoir rocks indicates that CO_2 storage potential is likely to be low, and possibly non-existent, despite the thick and widespread sedimentary fill of the basin. However, given the vast area that the basin covers it is probably premature to write it off completely.

References

Prasad, B. & Verma, K.K. 1991. Chapter 4 Vindhyan Basin: A Review. In: Tandon, S.K., Pant, C.C. & Casshyap, S.M. (editors), *Sedimentary basins of India: Tectonic Context.* Gyanodaya Prakashan, Nainital, India, pp50-62.

Peters, J., Bhatnagar,, P.K. & Singh, S.K. 1997. Potential Fractured Reservoirs in the Vindhyan Super Group and their Relation to Petrographic Characteristics. *Proceedings of Second International Conference and Exhibition, Petrotech 97*, New Delhi, pp. 239-248. B.R. Publishing Corporation, New Delhi.

Srivastava, B.N., Rana, M.S. & Verma, N.K. 1983. Geology and Hydrocarbon Prospects of the Vindhyan Basin. *Petroleum Asia Journal*, Nov. 1983, 179-189.

Appendix 4 Comparison of saline aquifer CO_2 storage potential of India, Pakistan and Bangladesh with that of the European sector

In the IEAGHG R&D Programme study of the CO_2 storage in the European Sector (Wildenborg et al. 2005) the CO_2 storage capacity in deep saline aquifers where the reservoir thickness and distribution was unknown was estimated as follows:

It was assumed:

1. That one or more deep saline aquifers suitable for CO_2 storage were present over 50% of the basin.
2. 0.2 x 10^6 tonnes CO_2 could be stored per km^2 of the area above.

Multiplying the above gives a crude estimate of the CO_2 storage potential. This methodology assumes that the storage capacity of a sedimentary basin depends on its area rather than its geology – a gross oversimplification. When this methodology is applied to those basins in India, Pakistan and Bangladesh that have good and fair saline aquifer CO_2 storage potential, it produces the results shown in Table 1.

Table A4. 1 Estimated saline aquifer CO2 storage capacity using European Sector methodology

Country/Basin name	Area km^2	Estimated saline aquifer CO_2 storage capacity 10^6 tonnes
India		
Assam Basin	56000	5600
Assam-Arakan fold belt	68000	6800
Mahanadi Basin*	86000	8600
Krishna-Godavari Basin*	40000	4000
Cauvery Basin*	60000	6000
Mumbai Basin*	120000	12000
Cambay Basin	56000	5600
Barmer Basin	10000	1000
Kutch Basin*	71000	7100
Jaisalmer Basin	30000	3000
Bikaner-Nagaur Basin	36000	3600
Subtotal India		*63300*
Pakistan		
Indus Basin		0
Balochistan Basin	300000	30000
Subtotal Pakistan		*30000*
Bangladesh		
Bengal Basin (E Bangladesh)**	200000	20000
Subtotal Bangladesh		*20000*
Total		**113300**

*Includes offshore areas to 200 m isobath, **including Chittagong Hill Tracts

For comparison, the total saline aquifer CO_2 storage capacity of the European sector (Iceland, Norway, Sweden, Finland, Denmark, Ireland, UK, Netherlands, Belgium, Luxembourg, Germany, France, Austria, Switzerland, Portugal, Spain, Italy and Greece) is estimated to be 150 Gt CO_2 (Wildenborg et al. 2005).

Appendix 5 Information sources used to update the IEAGHG R&D Programme CO_2 sources database

5.5 INDIA

5.5.1 General data

CMIE Centre for Monitoring Indian Economy http://www.cmie.com.

Google Earth http://www.earth.google.com.

Energy Manager and Energy Auditor portal http://www.energymanagertraining.com.

Geographic and Geospacial information for locations around the world http://www.earthsearch.net, http://www.traveljournals.net, http://www.worldgazetteer.com, http://fallingrain.com/world/, http://dss.ucar.edu/datasets/ds480.1/inventories/daily

Teri Energy Data Directory and Year Book (TEDDY) 2004-05. Published by Teri Press.

5.5.2 Fertiliser

Annual Report 2005-06, Ministry of Chemical and Fertilizer.

Katja. S, Jayant.S.1999. Indian Fertilizer Industry: Productivity and Energy Efficiency. Lawrence Berkley National Laboratory.

Ministry of Chemical & Fertilizer http://www.fert.nic.in

Handbook on Fertilizer Technology, Fertilizer Association of India.

Cement

Annual Report 2005-06. Gujarat Ambuja Cements Ltd.

Annual Report 2005-06. Madras Cements Ltd.

Annual Report 2005-06. UltraTech Cement.

ICRA Sector Analysis July 2006. www.icra.in

Cement Manufacturers Association http://www.cmaindia.org

Iron and Steel

Annual Report 2005-06. Ministry of Steel.

Ministry of Steel http://www.steel.nic.in.

Annual Report 2005-06. Steel Authority of India Limited.

ABN AMRO Sectoral Reports by Ajit Ranade and Sanchita Das.

World Steel Review, Iron & Steel Statistics Bureau, February 2007.

Annual Report 2005-06. TATA Steel Ltd.

Annual Report 2005-06. Jindal Steel & Power Ltd.

Annual Report 2005-06. Ispat Industries Ltd.

Annual Report 2005-06. Usha Martin Ltd.

Annual Report 2005-06. Jayaswals Neco Ltd.

Annual Report 2005-06. Kalyani Steels Ltd.

Annual Report 2005-06. Tata Metaliks Ltd.

ICRA Sector Analysis. July 2006. www.icra.in

Refinery

Ministry of Petroleum and Natural Gas http://www.petroleum.nic.in

Annual Report 2005-06. Ministry of Petroleum and Natural Gas. http://www.petroleum.nic.in

Annual Report 2005-06. Indian Oil Corporation Limited (IOCL) http://www.iocl.com

Annual Report 2005-06. Chennai Petroleum Corporation Limited (CPCL). http://www.cpcl.co.in

Annual Report 2005-06. Hindustan Petroleum Corporation Limited (HPCL). http://www.hindustanpetroleum.com

Annual Report 2005-06. Bharat Petroleum Corporation Limited (BPCL). http://www.bharatpetroleum.com

Annual Report 2005-06. Reliance Petroleum Ltd. (RPL). http://www.ril.com

Annual Report 2005-06. Oil and Natural Gas Commission. http://www.ongcindia.com

Power

All Indian Electricity Statistics .General Review 2006. Central Electricity Authority.

Central Electricity Authority. http://www.cea.nic.in

Annual Report 2005-06. Ministry of Power. http://www.powermin.nic.in

Ministry of Power. http://www.powermin.nic.in

Power Finance Corporation http://www.pfc.gov.in