New potential carbon emission reduction enterprises in China

-- Deep geological storage of CO2 emitted through industrial usage of coal in China

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Abstract

Deep geological storage of carbon dioxide (CO_2) could offer an essential solution to mitigate greenhouse gas emissions from the continued use of fossil fuels. Currently, CO_2 capture is both costly and energy intensive; it represents about 60% of the cost of the total carbon capture and storage (CCS) chain which is causing a bottleneck in advancement of CCS in China. This paper proposes capturing CO_2 from coal chemical plants where the CO_2 is high purity and relatively cheap to collect, thus offering an early opportunity for industrial-scale full-chain CCS implementation. The total amount of high concentration CO_2 that will be emitted (or is being emitted) by the coal chemical factories approved by the National Development and Reform Commission described in this paper is 42 million tonnes. If all eight projects could utilize CCS, it would be of great significance for mitigating greenhouse gas emissions in China. Basins which may provide storage sites for captured CO_2 in North China are characterized by large sedimentary thicknesses and several sets of reservoir-caprock strata. Some oil fields are nearing depletion and a sub-set of these are potentially suitable for CO_2 enhanced oil recovery (EOR) and CCS demonstration but all these still require detailed geological characterisation. The short distance between the high concentration CO_2 sources and potential storage sites should reduce transport costs and complications. The authors believe these high purity sources coupled with EOR or aquifer storage could offer China an opportunity to lead development in this globally beneficial CCS option.

Keywords: Capture; CCS; China; coal; CTL; storage

1. Introduction

China is the world’s greatest energy consumer and also the world’s largest coal producer.[1] Currently, coal is the main energy source, representing 77% of primary energy production and 70% of the total fuel consumed in China[2] and it is expected that coal will remain the main energy source for China for decades to come. For this reason, much of the CCS research in China has focused on coal-fired power generation and coal-based industries. However, previous research has not considered the rapid development of industrial-scale conversion of coal to liquid (CTL) products such as gas or olefin over the past few years in China. This rapid expansion occurred in response to shortages in the supply of oil and rapidly rising global oil prices. Coal-based synthetic natural gas, for example, has benefitted from growth in demand and rising prices in the Chinese natural gas market. These coal chemical industries emit large amounts of high concentration CO_2 which is currently disposed of into the atmosphere.

The authors believe that the high cost of post-combustion CO_2 capture from power plant flue and the high cost and lack of maturity in pre-combustion capture of CO_2 is causing a bottleneck in the deployment of CCS in China.[3-5] The high purity-CO2 produced from these coal chemical plants could be captured more cheaply than CO_2 from lower purity sources, thereby assisting the growth of CCS in China. If this relatively cheap CO_2 could offer further financial benefit such as for enhanced oil recovery (EOR), this would also support investment in CO_2 capture research in China. The authors suggest that these sources are therefore of great interest for CCS and so potential storage sites near these chemical plants should be sought.

In this paper, the authors first present the location and calculated emissions for coal chemical plants which have been approved by the National Development and Reform Commission (NDRC), China, some of which are already under construction. Then basins near these sources are screened in terms of suitability for CO_2 storage and storage potential is calculated. Finally, the authors discuss what this could mean for CCS in China and how CCS linked to coal chemical plants globally could reduce emissions.

2. Chemical coal industries in China

In recent years, the rate of demand for oil has outstripped national supply which has promoted rapid development of the coal chemical industry. Hot spots of coal-based industrial development have focused on regions with abundant coal reserves such as the Xinjiang, Inner Mongolia, Shaanxi, Ningxia and Shanxi provinces (and Autonomous Regions). The low price of coal and proximity to coal mining districts make coal to gas/liquid/olefin products economically viable. The coal to gas, liquid and olefin projects which have been approved by the NDRC are described in Table 1.

There are four coal to coal-based synthetic natural gas (SNG) Projects with the total amount of synthetic natural gas produced being 15.1 Billion m^3 per year.[6-8] The amount of CO_2 emitted during coal to SNG processing is dependent on coal rank and technology amongst other factors. Based on expected emission factors (such as those used by IEAGHG) it was estimated that 214 000 tonnes[*] CO_2 with about 90% concentration are emitted for every 100 Mm^3 natural gas produced[9]**.** These four SNG projects would be expected to emit around 32 Mt (million tonnes) of CO_2 per year in total.

There is one NDRC-approved coal to liquid (CTL) project, it was estimated that 3.5 tonnes of CO_2 with about 90% concentration would be emitted per tonne of oil produced. Therefore, the total amount of CO_2 emitted by this plant was estimated to be 3.78 Mt per year. Sales of CTL products are welcome on the market due to their premium quality; the Shenhua Ordos CTL Branch easily obtained its license from China's Ministry of Commerce as a wholesaler for oil products.

There are three approved coal to olefin (CTO) projects which would be expected to produce about four tonnes of CO_2 with a concentration of about 90% would be emitted per tonne of polypropylene produced. The total amount of CO_2 emitted from these projects was estimated to be 6.4 Mt per year.

3. Site screening of geological storage options

Research required to screen deep saline aquifers for CO_2 storage includes the geological setting (such as geological structure, tectonic activity, heterogeneity, lithology, sensitivity, etc), reservoir conditions (such as salinity, sweep efficiency, reservoir depth and thickness, porosity and permeability), source-sink matching and assessment of the cost and the

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[*] The authors assumed 2.14kg CO_2 would be emitted when 1 cubic metre of SNG is produced, therefore, 214,000 t CO_2 will be emitted when 100 M cubic metres of SNG are produced.

geological risks. Previous research in the EU-funded COACH and NZEC China-EU collaborative projects has also indicated that there is potential for storage in the Bohai,[10] Songliao, Subei and Qinshui Basins in north-east China.[11-15] A similar approach to the initial screening undertaken in those studies was applied here. Basins near the coal chemical plants described earlier in this paper were screened for suitability based on proximity to the sources and the presence of porous and permeable sandstone-rich formations with large areal extent at depth, capped by impermeable layers. Basins identified by this screening process included Bohai Bay Basin, Eren Basin, Ordos Basin (including Hetao Basin) and Junggar Basin. These basins include potential reservoir and caprock sedimentary sequences, which could make the basins possible sites for CO_2 storage (Fig. 1). A summary of the stratigraphical successions in the Bohai Bay, Ordos, Hetao and Junggar basins is given in Figs 2 - 5 and selected geological data relevant to CO_2 storage are given in Table 2. More detail on results of the basin screening is given below.

Storage potential in the central Bohai Basin was identified by the COACH project. For this paper, the Western sub-basin in the Xialiaohe Depression of the Bohai Bay Basin was also considered as it contains porous sandstone and conglomerate rich formations with thickness varying from tens to several hundreds of metres (Fig. 2). These are sealed by mudstones and lithological and structural traps could also potentially store CO_2 from the Datang Group Fuxin City CTG plant which is currently under construction. Fuxin City is also close to the Shuguang and Huanxiling oil fields (80 km) and Damintun Oil field (100 km). Initial exploitation of these oilfields began in the 1970s.[16] There are three sets of caprock - storage pairs developed in Liaohe Oil Field complex. From the oldest to youngest these are**:**

- Caprock in the third member of Shahejie Formation and storage in the fourth member of the Shahejie Formation plus the Kongdian Formation;

- Caprock in the first member of Shahejie Formation and storage in the second member of Shahejie Formation;
- Caprock in the Minghuazhen Formation and storage in the Guantao Formation.

Therefore, there are three sets of regional storage-seal pairs potentially available for CO_2 storage: the upper is the Guantao Formation – Minghuazhen Formation; the middle is combined sub-reservoir-caprock pair of Eocene age; the deepest is the Buried Hill carbonate Formation (the Wumishan Formation in Jixian system of middle-upper Proterozoic age).

Eren basin is a strongly heterogeneous continental basin with generally low porosity and low permeability. There are two sub-basins however, which could have some storage potential; the Manite and Tengger sub-basins where there are sandstone rich formations that are hundreds of metres thick. The Datang Group Hexigten Qi coal to gas factory is located less than 100 km from the Tengger sub-basin.[17,18] In these sub-basins, the sandstone reservoir formations are buried at depths of 1–3km and potential storage sites are formed by structural and fault traps.

A pilot project storing 100 000 tonnes of CO_2 emitted by Shenhua DCL plant was launched in January, 2011. The CO_2 is injected into a saline aquifer formation in Wulanmulun Zhen, Ejinhoro Qi (county) in the Ordos Basin. This project is being carried out by the Shenhua Group and is not discussed further in this paper as it is already undertaking CO_2 storage.[20] However, another coal to olefin plant, Ningdong factory located in Lingwu City, lies 40 km from Majiatan Oil Field and 38 km from Lizhuangzi Oil Field. It could also be considered as a potential capture target for storage of CO_2 in oilfields and surrounding aquifers in the same basin where there are sandstones around 200 m thick at suitable depth and potential structural and lithological traps (Fig. 4).

The coal to olefin factory in Baotao City is located in the Hetao Basin (Fig. 1, Fig. 3). In the Hetao Basin, mudstone interbedded with fine-grained sandstone of the Pliocene Wulantuke Formation and mudstone intercalated with fine-grained sandstone and marlite of the Miocene Wuyuan Formation form the caprock and silt to medium-grained sandstone of the Oligocene Linhe Formation (thickness 260–340 m) offer a potential storage site in the Huhe Depression of the basin with structural and lithological trapping potential.[19]

The coal to gas factory under Qinghua Coal Chemical Engineering Corporation located in Yining County, Xinjiang lies about 250 km from the Yining and Dushanzi Oil Fields in the Junggar Basin where there is potential for CO_2 storage in sandstones in structural antiformal closures and lithological trapping[21] (Fig. 5), however the sandstones here are only 17 m thick, so this may not be a promising site.

4. Geological storage calculations

4.1 CO_2 storage during CO_2-EOR

During carbon dioxide enhanced oil recovery (CO_2-EOR) operations, some CO_2 is stored in the oil reservoir. The additional oil recovered is calculated as a percentage of the original oil in place (OOIP) which comes into contact with the injected CO_2. Stevens[22] estimated that about 75% of the OOIP would be in contact with the CO_2 during miscible or immiscible flooding. The method used by Stevens[22] was modified by the authors and used to calculate the potential for EOR[23] in the Liaohe Oil Field complex of the Bohai Bay Basin (Fig. 6).

The authors calculated the incremental oil production through CO_2-EOR assuming that the oil recovery rate was 8%, 10% and 15% of the OOIP. The potential CO_2 storage capacity in other oil fields during CO_2-EOR operations in China could also be estimated for other fields using this method where data are available.

4.2 CO_2 storage potential in deep saline aquifers.

All the sites selected through the basin-screening have suitable geological characteristics and initial volumetric estimates suggest they could store CO_2 emissions from the nearby coal chemical plants for many decades. The next step is further site characterisation and full assessment of the storage capacity by obtaining detailed geological data from new seismic data or borehole records.

Globally, a number of methods to calculate the CO_2 storage capacity in deep saline aquifers have been put forward, including the CSLF (Carbon Sequestration Leadership Forum), USDOE (United States Department of Energy) and others,[24-26] but there is no single agreed methodology. Additionally, most of these methodologies include a ‘storage factor’ of some description which includes a number of factors (such as irreducible water saturation or sweep efficiency), the values of which are not generally known for aquifer storage sites since they are generally less well studied than oil fields. A more detailed site characterisation is now required which may include 2D and 3D seismic data acquisition and further drilling of exploration wells to suit the nature of different regions and different storage sites in China where these data are not available. As identified from the COACH and NZEC projects, the basin lithology and structure is often complex and will be challenging to characterize and to utilize for CO_2 storage.

Some of the oilfields have undergone extensive water flooding, for example, the Buried Hill oil fields[†] have been exploited on a large-scale since the 1970s and are in the late stages of development; most the oil in place has been extracted and the injected/native water has intruded into the oil fields to such an extent that it could be considered appropriate to estimate storage capacity of deep reservoirs in the Huabei oil field complex of the Bohai Bay Basin using the saline aquifer calculation. The average total effective thickness of the 13 Buried Hill reservoirs could be considered as the total thickness of saline aquifer formations (i.e. about 65 m) to estimate the storage capacity. In the Buried Hill reservoirs, porosity comprises inter-granular pores and dissolution features in the dolomite and limestone seams. In the original assessment of hydrocarbon reserves, the average porosity was calculated to be 6%. This figure was used for calculating storage capacity. Irreducible water saturation was estimated to vary from 10-50%.The storage capacity was 573 to 953 million tonnes CO_2 in the Buried Hill reservoirs and more than 1 billion tonnes in the sandstone-rich Guantao Group.[27]

5. Conclusions: New enterprises and new vista

The trend of high oil prices on international markets has strongly supported development of coal chemical industries in China. CTL, gas and olefin processes produce highly concentrated CO_2 streams. Capturing these waste gases would help to reduce greenhouse gas emissions to realize more environmentally sustainable development. Capturing CO_2 emitted from coal-based chemical industries for CO_2-EOR or for storage could be an effective approach for reducing greenhouse gas emissions in China and could help overcome the current developmental bottleneck of high costs for CCS when and where these high concentration streams of CO_2 are readily available. Following the example set by the pilot scale in the

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[†] Buried Hill oilfields describes a common structural form for oilfields in China – i.e. hydrocarbons are trapped against an erosional surface which used to be a hilly palaeo-geographical surface

Ordos Basin project, the coal chemical industry could offer an early opportunity for industrial scale full chain CCS implementation in China.

Carbon dioxide captured from these coal chemical processes could be stored in adjacent sedimentary basins where they have suitable geological characteristics. The basins identified in this paper in Northern and Eastern China are characterized by large sedimentary thicknesses, tectonic stability and several sets of reservoir-caprock pairs, they also include some oil fields that are nearing depletion and a sub-set of these are potentially suitable for CO_2-EOR and CCS demonstration but require detailed geological characterisation. The short distance between the high concentration CO_2 sources represented by the coal-based chemical industries and storage sites should reduce transport costs and complications. Geographical relief is generally gentle, the wide grasslands and low relief hills are favourable for construction of the coal chemical plants as well as pipelines or roads for transport of raw materials and products. A CCS with EOR pilot using a coal chemical plant in North Shaanxi Province is being undertaken by Shaanxi Yanchang Petroleum (Group) Co., Ltd. and was supported by MOST in 2012.[28] This pilot, if successful, will prove the concept for future coal to liquid with CCS projects in China.

There is still the question of how much an energy company utilizing the CO_2 would pay as the CO_2 is currently disposed of as waste, and there are further questions about who would pay other costs such as capture and pipeline costs. The required investment capital, raw materials, energy and water consumption in coal-based industries are very high and their comprehensive utilization and environmental control requirements are rather strict. Project investment must be carefully considered based on coal resources, water resources, capital investment, transportation, sustainability and optimization of other factors (e.g. proximity to markets, coal source, water sources). Nonetheless, the authors believe there is still a good opportunity here as the CO_2 streams are high purity and therefore the costs of CO_2 capture, purification and compression will be low compared with those from flue gas in conventional coal-fired power plants.

The total amount of high concentration CO_2 that will be emitted by the coal chemical factories approved by the NDRC that have been described in this paper is 42 million tonnes. If all eight projects could utilize CCS, it would be of great significance for mitigating greenhouse gas emissions for China and globally. The authors hope that utilizing these high purity sources in China for carbon capture, utilization and storage (CCUS) in China could offer a good example for other countries rich in coal such as the USA, India, Germany and Poland. The IEA technology roadmap[29] estimates that 7% of the CO_2 emissions from primary energy supply in 2012 came from high purity sources such as natural gas processing and syngas generation and this is expected to grow to 23% by 2050 according to the ETP Baseline scenario. This expected increase in high purity sources could be highly significant for reducing greenhouse gas emissions if these are combined with CCS wherever practicable. If all the CO_2 from these sources could be captured and stored, based on the ETP Baseline scenario, global CO_2 emissions in 2050 could potentially be reduced by 3.7 $GtCO_2$.

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Table 1

Location	Project and product amount		Type	CO_2 emissions (Mt/Y)
Hexigten Qi,, Inner Mongolia AR. under construction	Datang Group, Hexigten Qi (Keshiketeng)	Phase I - 1.34 Billion m^3/y in 2011	CTG	Phase I – 2.86
		Phase II - 2.68 Billion m^3/y in 2012	CTG	Phase II – 5.73
		Phase III - 4 Billion m^3/y in 2014.	CTG	Phase III – 8.56
Duolun County Inner Mongolia AR (built and undergoing calibration)	Datang Group, Duolun County	0.5 Mt/y poly-propylene	CTO	2
Fuxin City, Liaoning Province, under construction	Datang Group, Fuxin City,	4 Billion m^3/y	CTG	8.56
Baotou City, Inner Mongolia AR (in operation)	Shenhua Group (Baotou)	0.6 Mt/Y olefin	CTO	2.4
Lingwu City, Ningxia Ningxia Hui AR (built and undergoing calibration)	Ningdong factory Shenhua Ningmei Group	0.5 Mt/y propylene	CTO	2
Ejinhoro Qi, Erdos City, Inner Mongolia AR, under construction	Huineng Group, Ejinhoro Qi,	1.6 Billion m^3/y	CTG	3.42
Ejinhoro Qi, Erdos City, Inner Mongolia AR (in operation)	Shenhua Group, Ejinhoro Qi,	1.08 Mt/Y (oil production)	CTL	3.78
Yining County, Xinjiang Uygur AR, under construction	Qinghua Coal Chemical Engineering Group, Xinjiang	Phase I – 1.37 Billion/Y	CTG	
		Phase IV – 5.5 Billion m^3/y	CTG	11.77

Note: AR - Autonomous Region, CTG – coal to gas, CTL – coal to liquid, CTO – coal to olefin

Table 2

CO_2 project and quantity (Mt/y)	**Basin**	**Area Km^2**	**Reservoir age and Type**	**Thickness m**	**Depth m**	**Reservoir Physical properties**		**Caprock**	**Hydrological conditions**		**Storage type**
						Porosity %	**Permeability MD**	**Lithology and thickness m**	**type**	**Salinity mg/L**	
Hexigten Qi 2.86 – 8.56 Mt/y, Duolun County, 2Mt/y	Manite and Tengger sub-basins, Eren Basin	22170	K1 Sandstone	Several hundreds of m	1000~ 3000	10-30	8-3922	Mudstone 100-356	NaHCO3	1756-5797	CO_2-EOR Saline aquifer
Fuxin City 8.56 Mt/y,	Bohai Bay Basin; Western sub-basin in the Xialiaohe Depression	427.6	Es Sand stone and conglomerate	Tens to several hundreds of m	700-3780	16-30	100-3000	Mudstone S1 0-945 S3 0-1861	NaHCO3	281-58107	CO_2-EOR
Baotou City 2.4 Mt/y	Hetao Basin, Huhe sub-basin	1500-2500	E K1 Sandstone	260-340 260- 310	1800-3500	10-25 4.9-11.7	274-302 1.4-47.7	Mudstone 400-800			Saline aquifer
Lingwu City 2Mt/y, Ejinhoro Qi Huineng Group 3.42 Mt/y and Ejinhoro Qi Shenhua Group 3.78 Mt/y	Lizhuangzi, Mafang, Hongjingzi Oil Fields and other sandstone formations Ordos Basin	150	J1y J1y2z Sand stone	200	870-2000	17.5-19	41.5-213.3	Mudstone 100-150	$CaCl_2$ $MgCl_2$ $NaHCO_3$ $Na2SO_4$	3900-80000	CO_2-EOR Saline aquifer
Yining County 11.77 Mt/y	Dushanzi Oil Field	1.2	N1s Sand stone	17	800-1800	17.6	0.8-46	Mudstone 200	$CaCl_2$ $NaHCO_3$	2000-37000	CO_2-EOR Saline aquifer

Figure 1. Sources of CO_2 (red) and main sedimentary basins (green) in the northern sedimentary basins of China. Basemap data taken from the Digital Chart of the World (1:1 million data) provided by ESRI, State province and basin outline reproduced with the kind permission of the USGS. 1 - Manite sub-basin, 2 - Tengger sub-basin, 3 - Xialiaohe Depression, 4 - Shuguang Oil field, 5 - Huanxiling Oil field, 6 - Wulanmulun Zhen, 7 - Yining County.

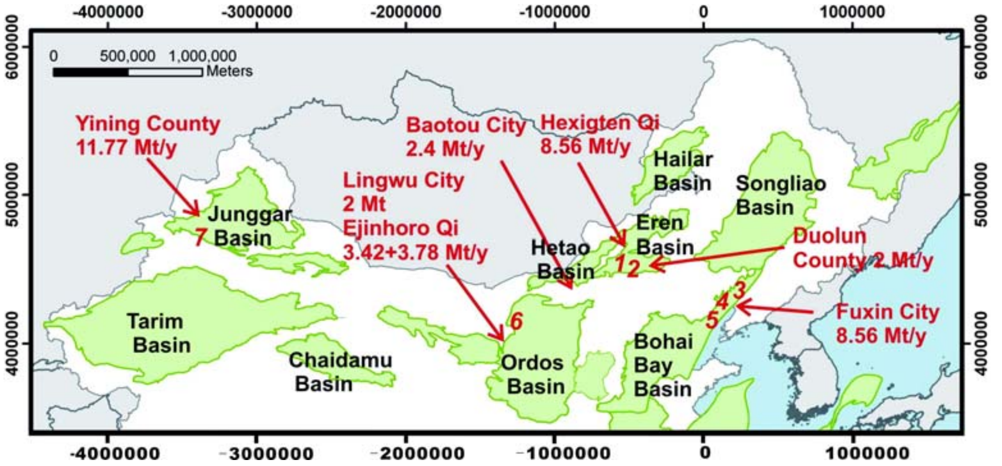
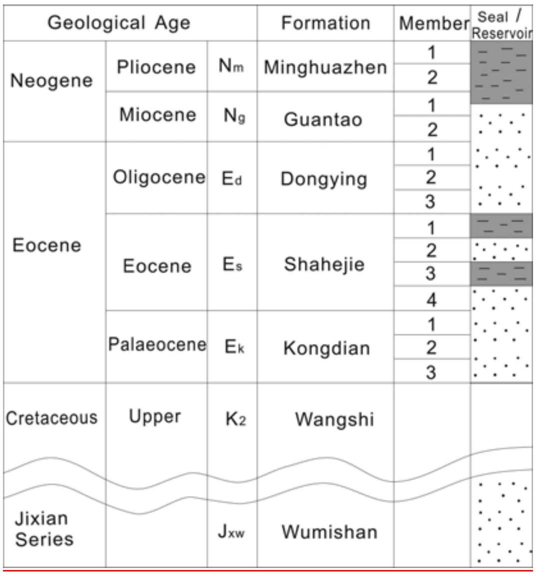
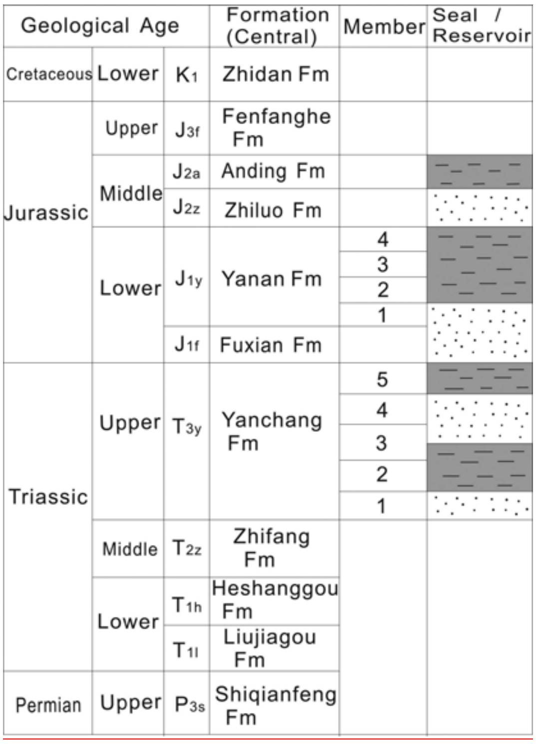


Figure 2. Simplified stratigraphy of Bohai Bay Basin.



Geological Age			Formation	Member	Seal / Reservoir
Neogene	Pliocene	N_m	Minghuazhen	1	▨
				2	▨
	Miocene	N_g	Guantao	1	⁘
				2	⁘
Eocene	Oligocene	E_d	Dongying	1	⁘
				2	⁘
				3	⁘
	Eocene	E_s	Shahejie	1	▨
				2	⁘
				3	▨
				4	⁘
	Palaeocene	E_k	Kongdian	1	⁘
				2	⁘
				3	⁘
Cretaceous	Upper	K_2	Wangshi		
Jixian Series		J_{xw}	Wumishan		⁘



Geological Age			Formation (Central)	Member	Seal / Reservoir
Cretaceous	Lower	K_1	Zhidan Fm		
Jurassic	Upper	J_{3f}	Fenfanghe Fm		
	Middle	J_{2a}	Anding Fm		▨
		J_{2z}	Zhiluo Fm		⁙
	Lower	J_{1y}	Yanan Fm	4	▨
				3	▨
				2	▨
				1	⁙
		J_{1f}	Fuxian Fm		⁙
Triassic	Upper	T_{3y}	Yanchang Fm	5	▨
				4	⁙
				3	⁙ ▨
				2	▨
				1	⁙
	Middle	T_{2z}	Zhifang Fm		
	Lower	T_{1h}	Heshanggou Fm		
		T_{1l}	Liujiagou Fm		
Permian	Upper	P_{3s}	Shiqianfeng Fm		

Figure 3. Simplified stratigraphy of Ordos Basin.

Figure 4. Simplified stratigraphy of Hetao Basin.

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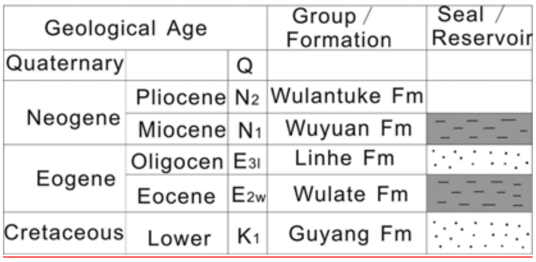
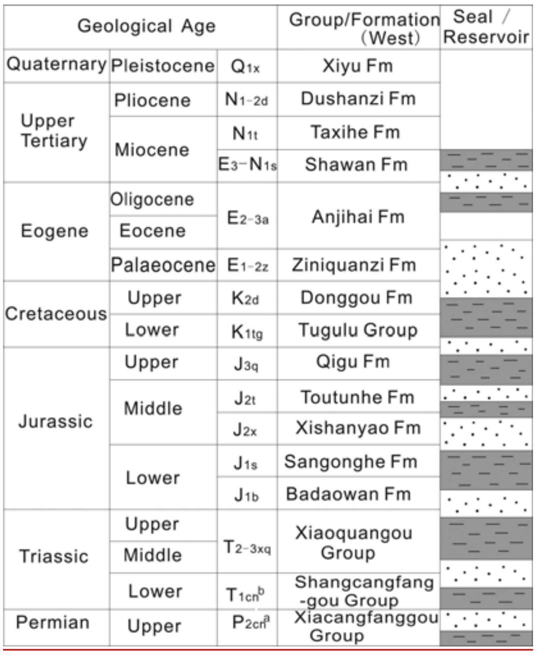


Geological Age			Group / Formation	Seal / Reservoir
Quaternary		Q		
Neogene	Pliocene	N_2	Wulantuke Fm	
	Miocene	N_1	Wuyuan Fm	▤
Eogene	Oligocen	E_{3l}	Linhe Fm	⁙
	Eocene	E_{2w}	Wulate Fm	▤
Cretaceous	Lower	K_1	Guyang Fm	⁙

Figure 5. Simplified stratigraphy of Junggar Basin.



Geological Age			Group/Formation (West)	Seal / Reservoir
Quaternary	Pleistocene	Q_{1x}	Xiyu Fm	
Upper Tertiary	Pliocene	N_{1-2d}	Dushanzi Fm	
	Miocene	N_{1t}	Taxihe Fm	
		E_3-N_{1s}	Shawan Fm	
Eogene	Oligocene	E_{2-3a}	Anjihai Fm	
	Eocene			
	Palaeocene	E_{1-2z}	Ziniquanzi Fm	
Cretaceous	Upper	K_{2d}	Donggou Fm	
	Lower	K_{1tg}	Tugulu Group	
Jurassic	Upper	J_{3q}	Qigu Fm	
	Middle	J_{2t}	Toutunhe Fm	
		J_{2x}	Xishanyao Fm	
	Lower	J_{1s}	Sangonghe Fm	
		J_{1b}	Badaowan Fm	
Triassic	Upper	T_{2-3xq}	Xiaoquangou Group	
	Middle			
	Lower	T_{1cn}^{b}	Shangcangfang-gou Group	
Permian	Upper	P_{2cn}^{a}	Xiacangfanggou Group	

Figure 6. Total calculated potential stored CO_2 (figures on the graph in red in Mt) for the Damintun, Shuguang, Huanxiling and Gaosheng oilfields of the Liaohe Oil Field complex which have a combined Original Oil in Place of 1071 Mt. EOR rate is extra oil recovered during EOR expressed in terms of a percentage of the OOIP. RCO_2 is the ratio of CO_2 injected to additional oil recovered.